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# **COIL - R&D WORKSHOP, Prague'99**

## **TECHNICAL PROGRAM**

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### **Monday 11 October**

9:00 - 9:30

Welcome and Organization affairs

#### **Session I**

**Chair : Gordon Hager**

9:30 - 10:10

Marsel V. Zagidullin

*„The completely scaleable 1 kW class supersonic COIL“*

10:10 - 10:50

Charles Helms

*„Recent experimental results on the RADICL laser“*

10:50 - 11:05

*Coffee break*

11:05 - 11:45

Otomar Špalek, Jarmila Kodymová, Vít Jirásek, Jan Kuželka

*„Recent experimental results on COIL device in the Institute of Physics“*

11:45 - 12:25

Frank Duschek et DLR colleagues

*„Results of water vapor measurements in the COIL gas flow“*

12:30 - 14:00

*Lunch break*

#### **Session II**

**Chair : Martin Stickley**

14:00 - 14:40

Dov Furman and Zamik Rosenwaks

*„Gain diagnostic in a supersonic COIL with transonic injection of iodine“*

14:40 - 15:20

Karin Grünwald et DLR colleagues

*„Results of COIL gain measurements“*

# REPORT DOCUMENTATION PAGE

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298-102

15:20 - 15:35      *Coffee break*

15:35 - 16:15

Boris Barmashenko and Ester Bruins

*„Iodine dissociation and small signal gain in supersonic COILs”*

16:15 - 16:55

Timothy J. Madden

*„An investigation of supersonic mixing mechanisms for the chemical oxygen-iodine laser (COIL)”*

16:55 – 17:35

Valery D. Nikolaev

*„The gas dynamic parameters and efficiency of mixing in COIL with array of supersonic nozzles”*

17:35 - 18:20

A separate meeting of the AFRL contingent with the Israeli Group for contract discussions

18:30      *Dinner*

## **Tuesday 12 October**

### **Session III**

**Chair : Charles Helms**

9:00 - 9:40

Gordon Hager

*„The measurement of gain on the 1.315  $\mu\text{m}$  transition of atomic iodine in a subsonic flow of chemically generated  $\text{NCl}(\alpha^1\Delta)$ ”*

9:40 - 10:20

Vít Jirásek, Jarmila Kodymová, Otomar Špalek

*„Thermodynamic and kinetic aspects of chemical generation of atomic iodine for a COIL and their consequences for experiments”*

10:20 - 11:00

Nikolai N. Yuryshev

*„A generation of atomic iodine for pulsed COIL by a dc discharge in alkyl iodides”*

11:00 - 11:15      *Coffee break*

11:15 - 12:00

A separate meeting of the AFRL contingent with the DLR Group for contract discussions

12:15 - 13:30      *Lunch break*

13:30 - 14:15

A separate meeting of the AFRL contingent with the Czech Group for contract discussions

14:15 - 14:45

**Round Table Discussion**

***Chair : Willy Bohn***

15:00      *Departure from Lanna to the Institute of Physics*

15:30 - 16:30

Visit of COIL laboratory

16:30      *Departure to the Hotel Schwaiger*

19:00      *Closing working dinner*

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**Notes:**

1/ A contribution will be given by the underlined colleagues

2/ A reserved time of 40 min for presentations includes the time for questions and discussion



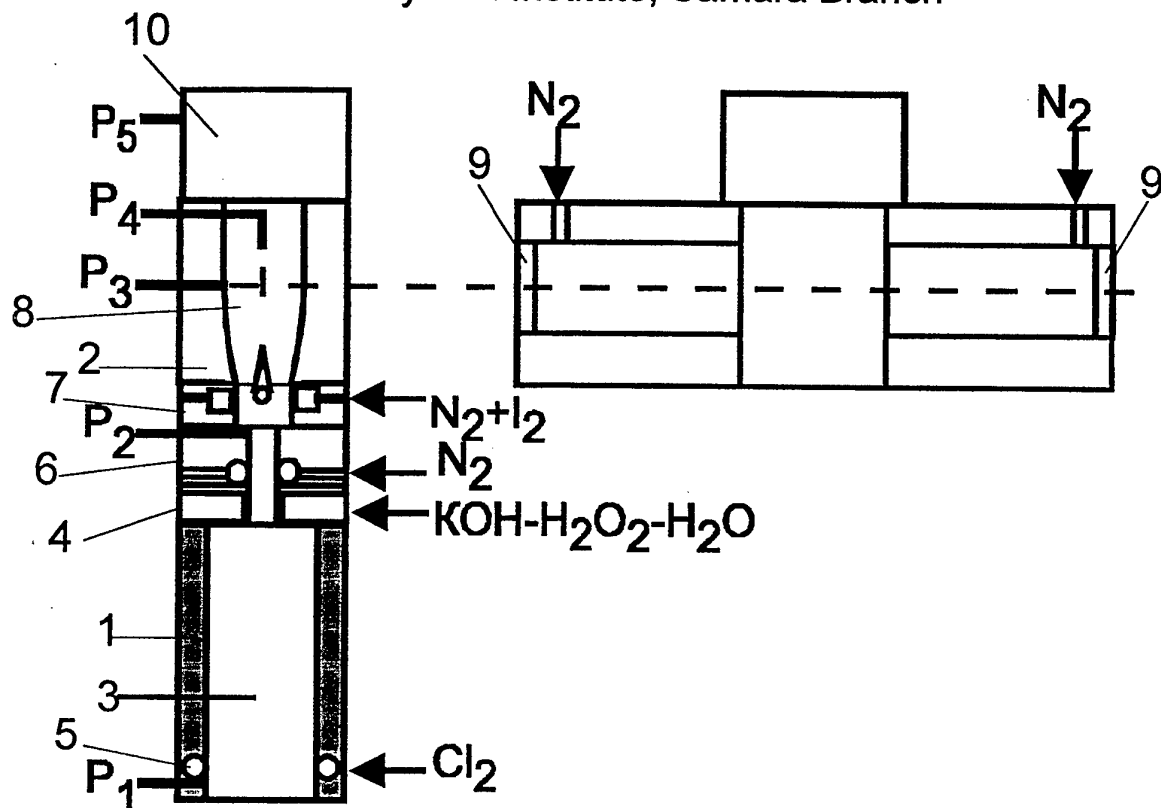


## The completely scalable 1 kW class supersonic COIL

*Zagladin M. V.*

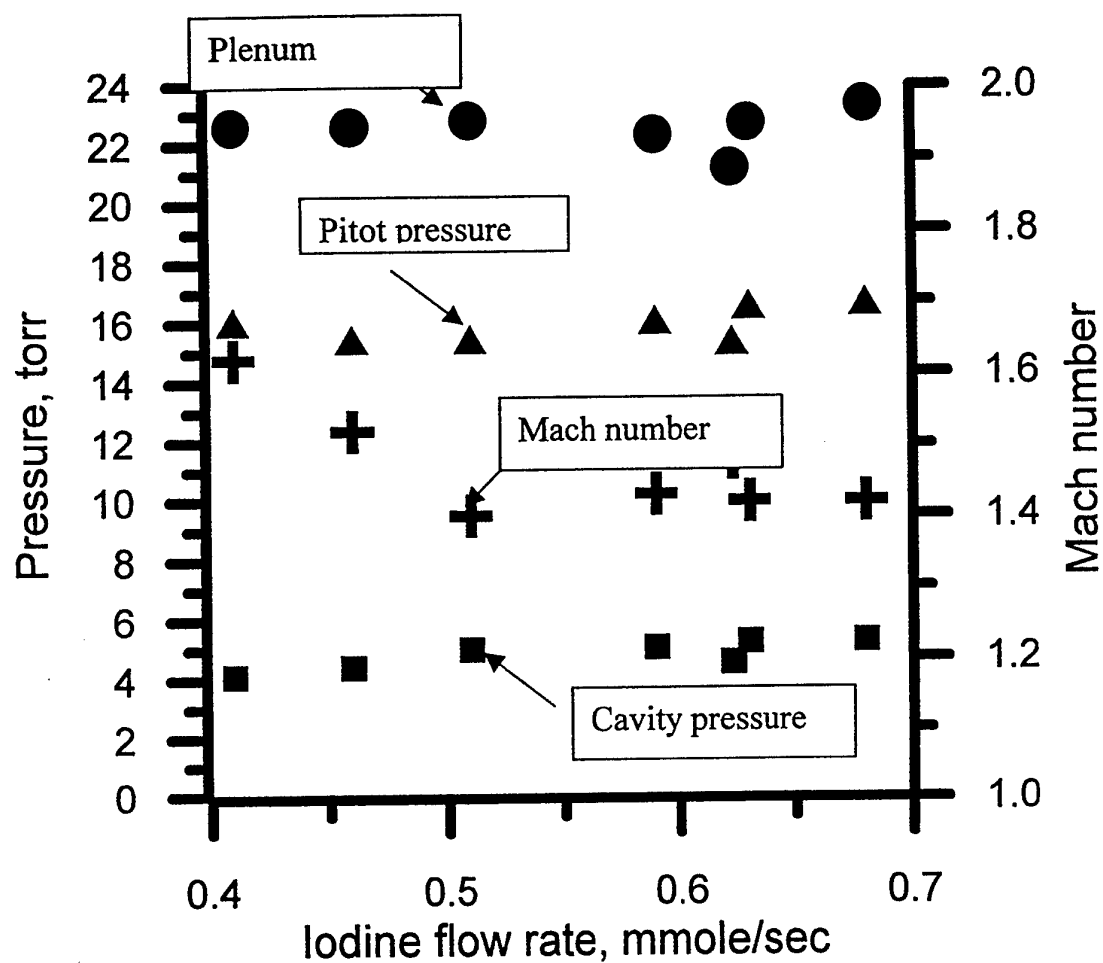
### Background

1. New compact Verty-JSOG operating stable up to 100 mmole/s of  $\text{Cl}_2$
2. Minimization of  $\text{O}_2(^1\Delta)$  losses when it is transported from JSOG to nozzle at high pressure and  $\text{N}_2$  dilution.
3. Optimization of geometry and gases flow rates.
4. COIL operation with slit nozzles because previously high efficiency was achieved with slit nozzle and 10 mmole/s of  $\text{Cl}_2$  and  $\text{N}_2$  dilution
5. Demonstration of high power with  $\text{N}_2$  dilution and 5 cm gain length and new Verty-JSOG.
6. Operation at minimal volume pump rate as possible
7. Scalability of COIL

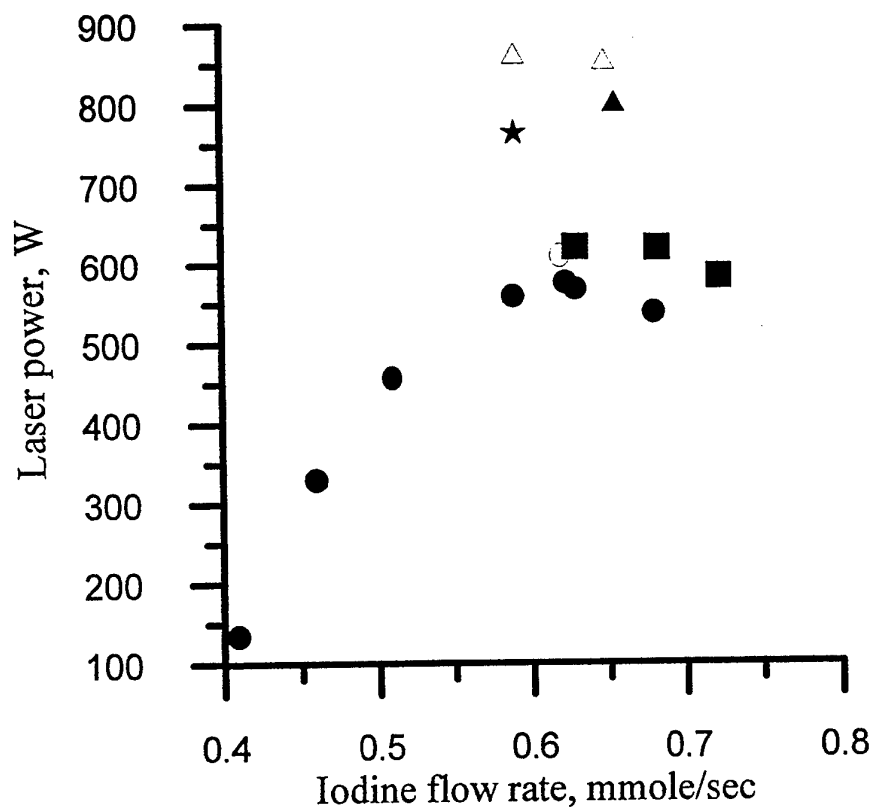


The set-up of COIL with Verty-JSOG and two slit nozzles

1- body of VJSOG ; 2- two slit nozzles ; 3 - counter-flow reactor ; 4- the nozzle bank for BHP jets ; 5-the inlet for  $\text{Cl}_2$ , 6- mixing chamber 6 ; 7- iodine mixer ; 8- laser cavity ; 9-mirrors ; 10-vacuum duct



Pressures in gas-flowing part of the laser and the Mach number.  
 $G_c:G_{N_2P}:G_{N_2S} = 1:2:1$ .  $G_c=39.2$  mmole/s., Pressure in JSOG 35 torr.



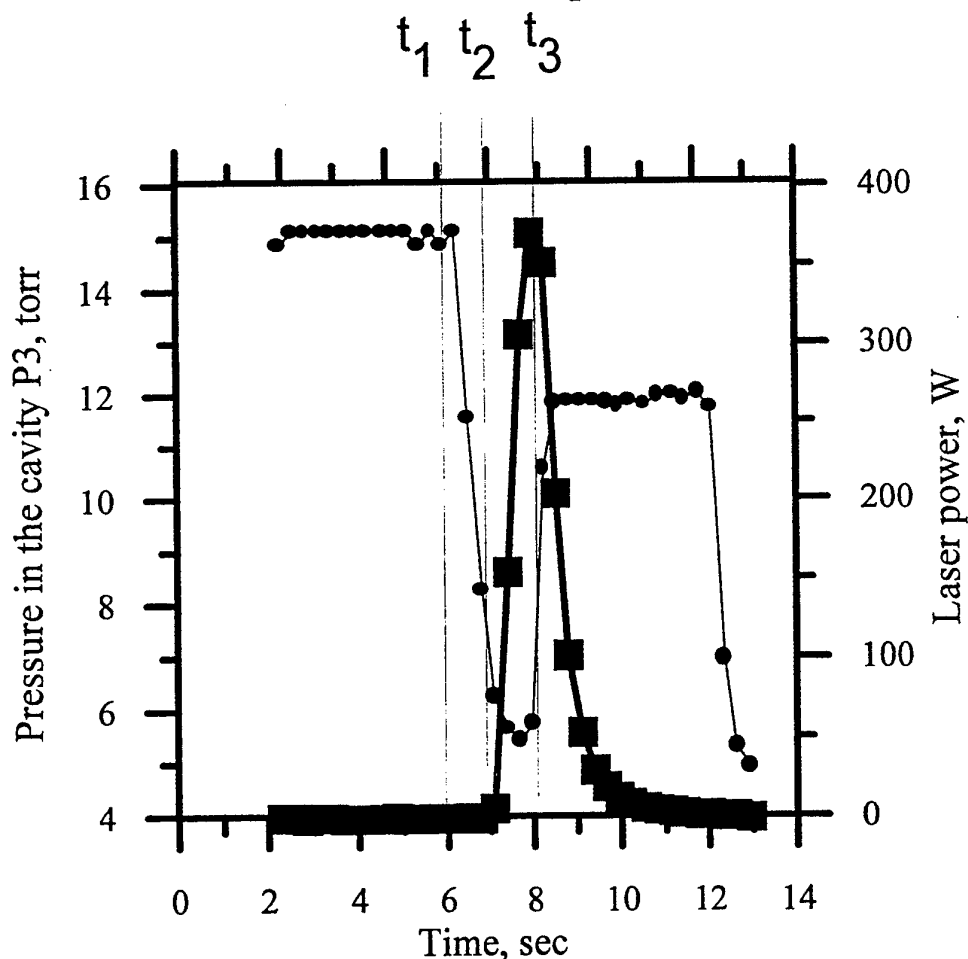
Dependence of output power on iodine flow rate and mirrors set at  $G_c:G_{N2P}:G_{N2S} = 1:2:1$ .  $G_c = 39.2$  mmole/s, Throat-optical axis distance  $L = 55$  mm

Symbol	T(N <sub>2</sub> P)	T <sub>1</sub> , %	T <sub>2</sub> , %
●	Room	0.9	0
○	Cold	0.9	0
■	Room	1.3	0
▲	Room	1	0
△	Cold	1	0
★	Room	0.7	0.7

1. Change the primary gas flow rate.

Then ratio of gas flows was  $G_c:G_{N_2P}:G_{N_2S} = 1:1:1$  to decrease pressure in JSOG and plenum pressure and decrease  $O_2(^1\Delta)$  losses.  $P_{SOG}=28$  torr, but lower Mach number and low power were obtained. At high  $I_2$  flow rate the subsonic flow in cavity and zero power were obtained.

2. Change the throat-optical axis distance up to  $L=80$  mm. The power 467W was achieved for  $GI_2=0.47$  mmole/s (higher than 370W for  $L=55$  mm). But for  $GI_2 > 0.54$  mmole/s the subsonic mode in cavity and zero power. Near  $GI_2 \approx 0.5$  mmole/s the unstable subsonic or supersonic mode in cavity.

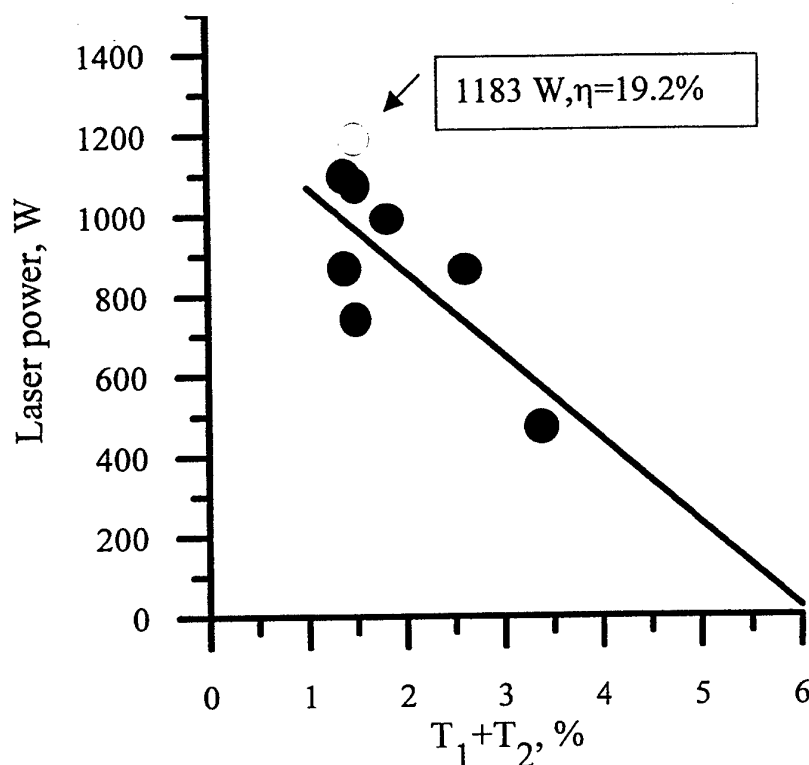


The transition from supersonic mode operation to subsonic mode. ● - pressure in the cavity,  $P_3$ , ■ - laser power,  $L=80$  mm.

# OPERATION OF COIL WITH 68 MMOLE/S OF CHLORINE

$G_c:G_{N_2P}:G_{N_2S} = 1:2:1$ .  $L=55$  mm.  $P_{SOG}=57$  torr, Plenum pressure 36 torr.

If  $N_2$  flow rate for mirror purging from 4.5 mmole/s to 10 mmole/s power from 890W to 1035W, Mach number from 1.49 to 1.39, cavity pressure from 7.6 torr to 9.7 torr.



Dependence of output power on the total mirrors' transmissivity for  $G_c = 68$  mmole/sec and  $G_{I_2} = 0.71$  mmole/sec. ● - primary nitrogen at room temperature, ○ - cold primary nitrogen.

Estimated threshold transmission 6% , estimated losses 0.5%, estimated SSG  $6.5 \times 10^{-3} \text{ cm}^{-1}$ .



## OPERATION OF COIL WITH 75 MMOLE/S OF CHLORINE

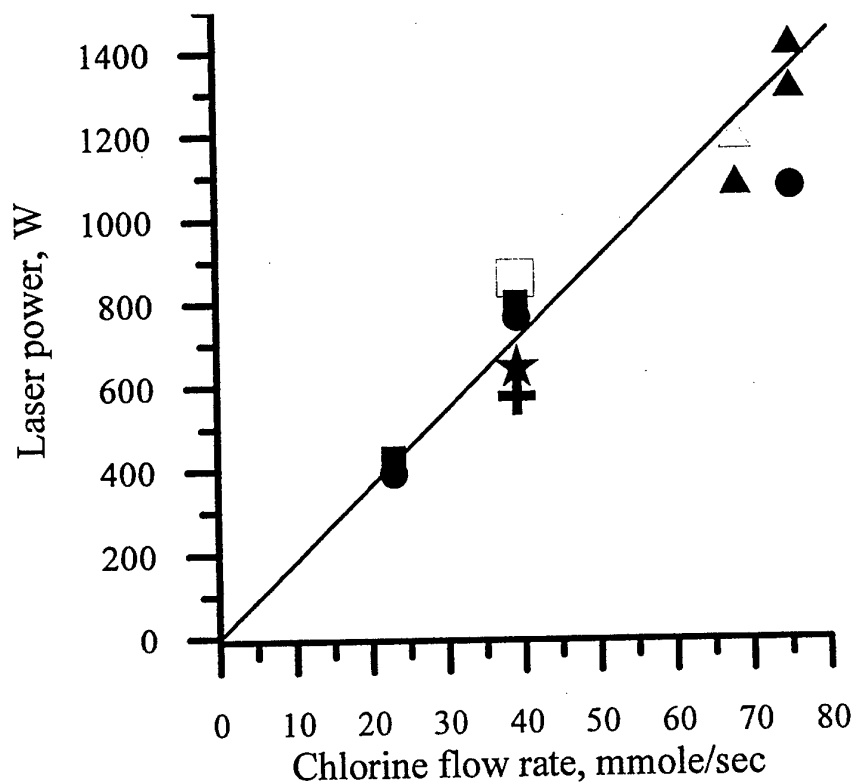
$G_c:G_{N2P}:G_{N2S} = 1:2:1$ .  $L=55$  mm.  $P_{SOG}=67$  torr, Plenum pressure 42 torr.

1. For  $N_2$  flow rate 2.7 mmole for mirror purging and  $GI_2=0.8$  mmole/s Mach number 1.5 but power 0.
2. For  $N_2$  flow rate 6.8 mmole/s for mirror purging and  $GI_2=0.89$  mmole/s power 1030W was obtained ( $\eta=15\%$ ), ( $T_1=0.94\%$ ,  $T_2=0.9\%$ )
3. The use of ratio  $G_c:G_{N2P}:G_{N2S} = 1:1:1$  resulted in to subsonic mode and 0 power.
4. The use ratio  $G_c:G_{N2P}:G_{N2S} = 1:1:0.58$  resulted in the same result.
5. The use ratio  $G_c:G_{N2P}:G_{N2S} = 1: 0.9 : 1.28$  resulted in 1303 W ( $T_1=0.8\%$ ,  $T_2=0.7\%$ ).
6. The use ratio  $G_c:G_{N2P}:G_{N2S} = 1 : 1.28 : 1.28$  resulted in 1408 W ( $T_1=0.8\%$ ,  $T_2=0.7\%$ ,  $GI_2=0.7$  mmole/s)

In last run mirrors were destroyed.

No cold primary  $N_2$  was used because we expected power more than 1500W and mirror destruction.

## SUMMARY OF RESULTS



Dependence of laser power on chlorine flow rate. The direct line corresponds to chemical efficiency of 20%.

$G_c$	$G_{N_2S}$	$G_{N_2P}$	$T_1, T_2, \%$	$W$	$\eta, \%$	$M$
23	23,2	46.5	0.7;0.7	390(●)	18.7	1.24
23	23,2	46.5	1; 0	429(■)	20.6	1.24
39.2	39,2	78.4	0.9;0	574(+)	16.2	1.48
39.2	43	78,4	1;0	798(■)	22.4	1.52
39.2	40	78,4	1.3;0	642(★)	18.1	1.51
39.2	39,2	78.4	0.7;0.7	764(●)	21.4	1.37
39.2	43	78.4*	1;0	858(□)	24.1	1.38
68	66	66	0.8;0.7	1074(▲)	17.4	1.51
68	66	66*	0.8;0.7	1183(Δ)	19.2	1.43
75	65.7	135.5	0.7;0.7	1074(●)	15.8	1.5
75	65.7	95.8	0.8;0.7	1303(▲)	19.2	1.4
75	82.	95.8	0.8;0.7	1408(▲)	20.7	1.5

\*- cold primary nitrogen



### Conclusions

1. The output power grows close to linearly when for chlorine flow rates from 23 mmole/s to 75 mmole/s
2. The effect of gas heating on gas flow was observed (transition from supersonic to subsonic operation).
3. The power 1.4 kW ( $\eta=20.7\%$ ) for 75 mmole/s and  $\eta=24.1\%$  (858W) for 39.2 mmole/s of  $\text{Cl}_2$  were achieved.
4. 5 kW per 1 liter of JSOG volume,  $\delta=100 \text{ W/cm}^2$ , 2.7 W per 1 L/s of exhaust pump capacity.
5. The estimated SS gain  $6 \times 10^{-3} \text{ cm}^{-1}$ .
6. Verty-JSOG is a good energy machine for COIL. The results obtained in this work can be as basis for comparison of other mixing-nozzles systems (reference point).
7. The gas flow section of high power COIL can be constructed as number of gas flow sections similar to considered.

# Predicting the Performance of RADICL using the 3-D MINT Code

Oct 11, 1999

Charles Helms

Gas and Chemical Lasers Branch (DELC)

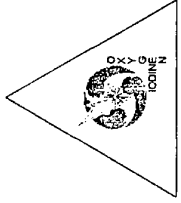
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# Contributors

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Alan Lampson

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## RADICL test team

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James Copland  
Vince Valdez  
John Oelfke  
Greg Johnson  
Teresa Neudecker

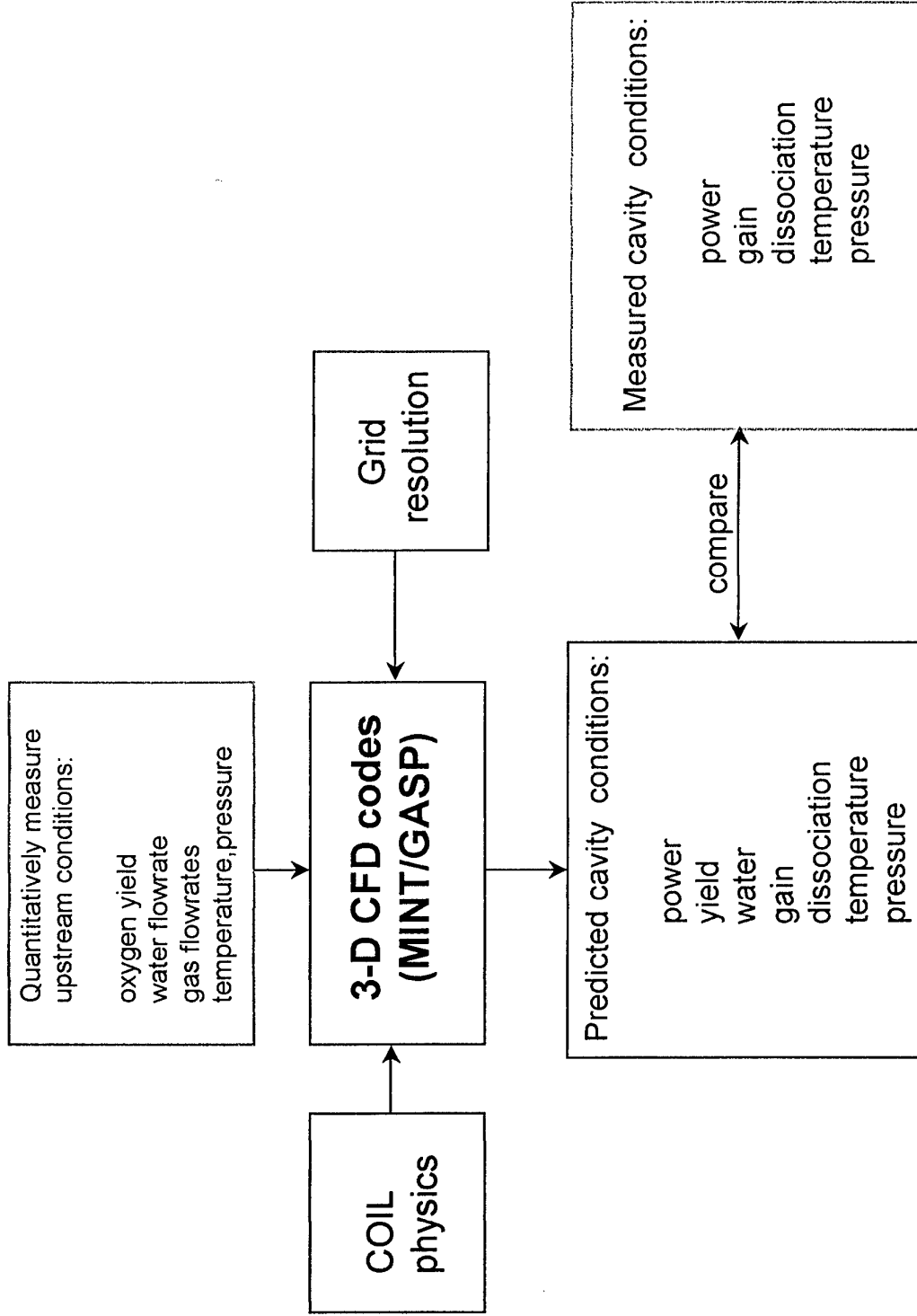
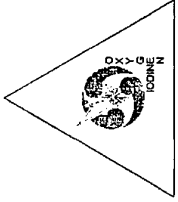
## DELC personnel

Kip Kendrick  
Gordon Hager  
Tim Madden  
Keith Truesdell

Physical Sciences Inc.



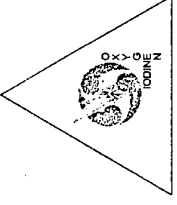
# Measurements and Models can be combined to test our understanding of COIL





# 3-D MINT 7-Pack Validation Effort

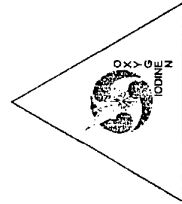
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- Goal: Determine the ability of the 3-D MINT code/kinetic rate package to predict the cavity conditions and power of the RADICL device at AFRL
- Approach:
  - Select a set of experimental conditions for which the results (power, gain, etc) are sensitive to the input flowrates
  - Carefully measure the input conditions and cavity conditions
  - Compare model predictions with experimental measurements



## 7 Selected RADICL Tests

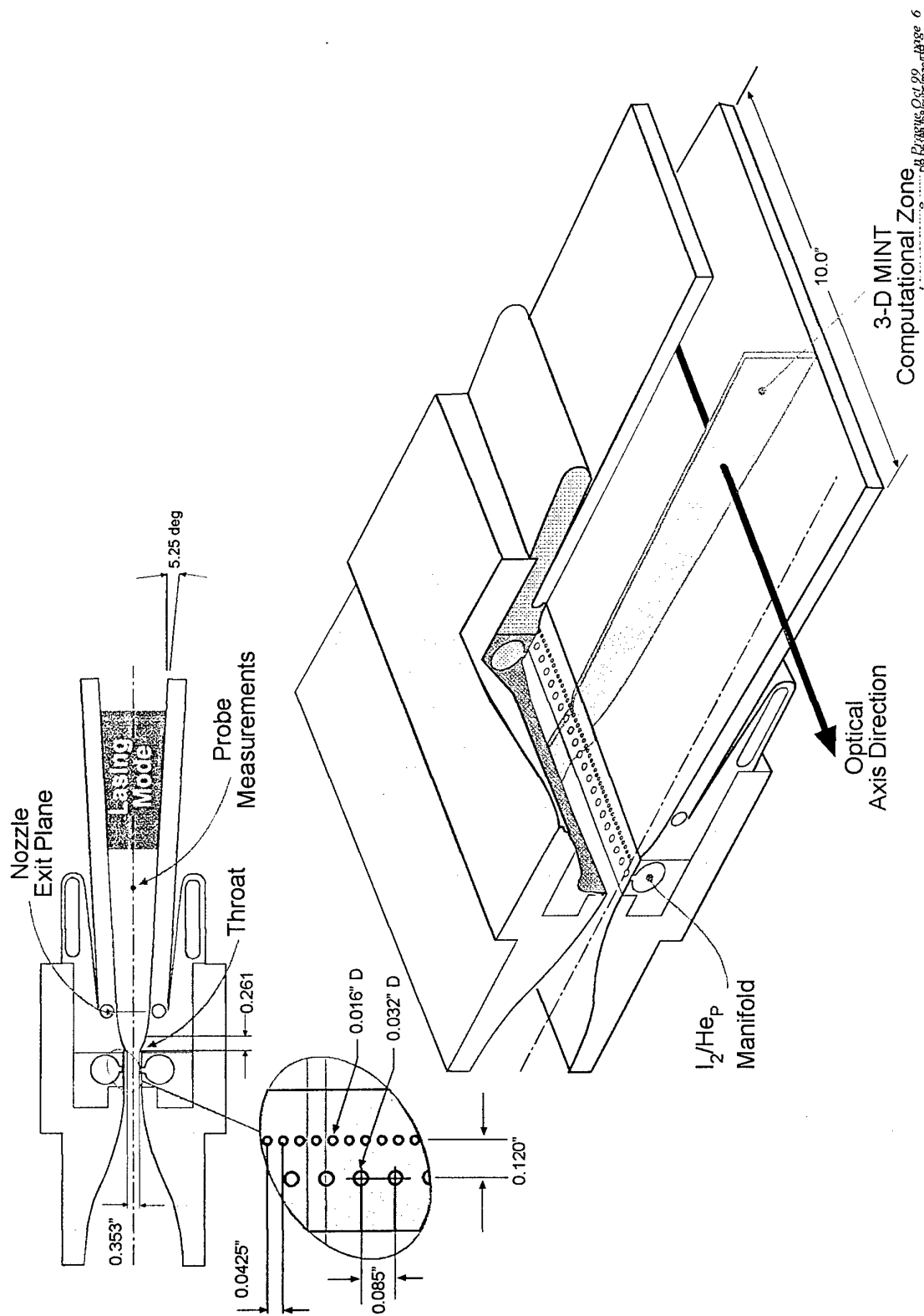
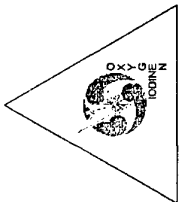


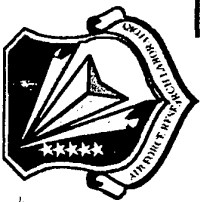
- 1) baseline\* ..... optimized iodine and penetration
- 2) low iodine ..... poor dissociation and power
- 3) high iodine ..... reduced power due to losses in dissociation
- 4) low iodine penetration ..... reduced power due to poor mixing of oxygen and iodine
- 5) high iodine penetration ..... poor dissociation and power
- 6) high diluent ratio ..... poor dissociation and power
- 7) high water ..... reduced power due to water quenching and condensation

\*.5 mol/sec Chlorine at 3/1 Helium/Chlorine

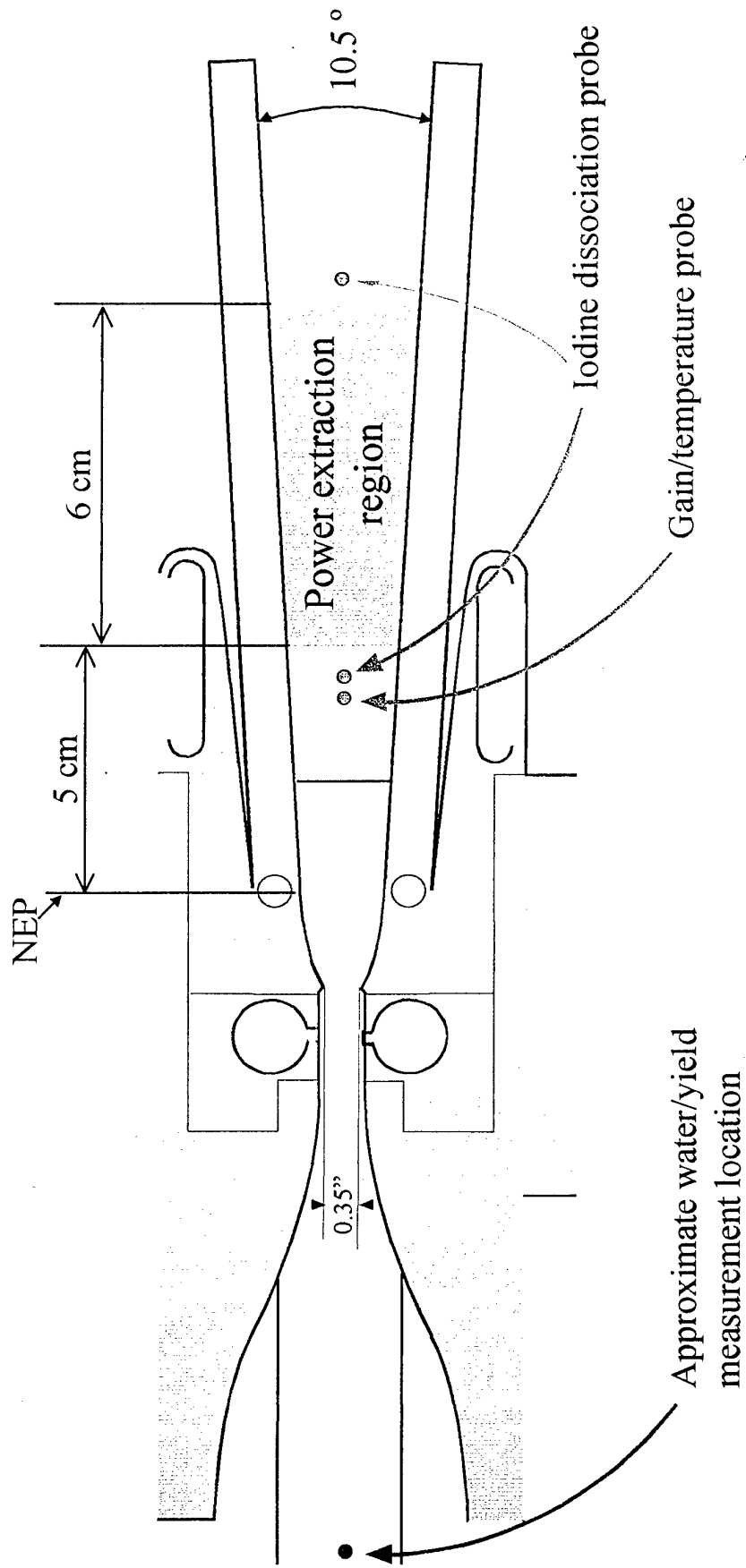
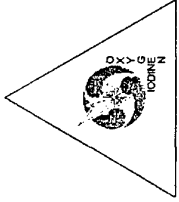


# RADICL 2-D SLIT NOZZLE CAVITY





# RADICL 2-D SLIT NOZZLE/ CAVITY



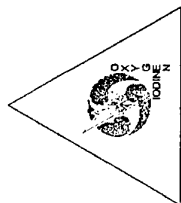
— 15" diameter rotating disk generator





# MINT Input Conditions for RADICL 7-Pack

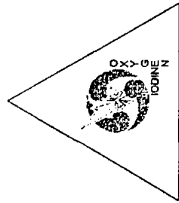
## Comparisons



Parameter	Case						
	1	2	3	4	5	6	7
Primary Cl <sub>2</sub> (mole/s)	0.507	.508	0.51	0.505	0.509	0.513	0.501
He <sub>0</sub> (mole/s)	1.513	1.492	1.52	1.513	1.52	2.937	1.479
H <sub>2</sub> O (mmole/s)	42	47	39	47	39	58	81
U	0.88	0.90	0.90	0.91	0.81	0.83	0.93
Y	0.41	0.415	0.41	0.458	0.376	0.48	0.405
P (Torr)	74.9	73.5	74.3	64.9	87.7	103	75.7
T (K)	315	319	316	312	318	294	333
Secondary I <sub>2</sub> (mmole/s)	6.56	4.1	9.75	6.64	6.35	5.5	6.54
Hes (mole/s)	0.776	0.848	0.69	0.313	1.405	1.235	0.781
P <sub>0</sub> (Torr)							
T <sub>0</sub> (K)	421	415	419	421	412	417	421
I <sub>2</sub> /O <sub>2</sub> (%)	1.49	0.897	2.15	1.49	1.39	1.29	1.40
Rate Parameter	4.2e-5	2.4e-5	7.0e-5	9.2e-5	2.6e-5	3.2e-5	3.9e-5
PEN (P <sub>s</sub> /P <sub>0</sub> )	4.8	4.7	4.7	2.7	6.5	4.9	4.7
PEN (AFRL)	0.14	0.14	0.14	0.09	0.19	0.14	0.14



# “7-pack” Experimental Cavity Conditions

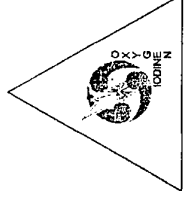


test description	ssg (%/cm)	cavity temp (K)	iodine dissoc upstream	iodine dissoc downstr.	power (kW)
baseline case	0.8	180	.94-.88	1	5.8
low iodine	.25-.45	145	.44-.37	1	2.7
high iodine	0.8	190	1	1	4.9
low penetration	0.4	185	0.99	0.98	4.3
high penetration	.35-.38	150-165	.31-.22	0.5	3
high diluent	0.22	150-160	.25-.15	0.29	1
high water	0.58	190-210	.86-.77	1	4.3



## 3-D MINT Code Features

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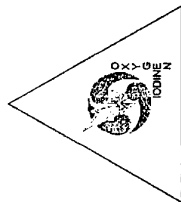


- 3-D implicit, time-dependent, Navier-Stokes model
  - Central difference ADI solution scheme with artificial viscosity
- Effective binary diffusion model with pressure diffusion
- Laminar flow analysis (K-E turbulence model option)
- COIL kinetics (10 species & 21 reaction set)
  - Heterogeneous I\* wall quenching included
- Finite rate condensation model including particle trajectory analysis
- Ray-trace stable resonator power model (or Fabry-Perot option)



# COIL Kinetics Package

(AFWL Reduced Mod 1 - with Temperature Dependence)

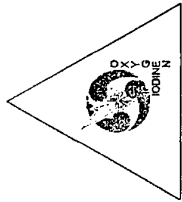


Reaction		$K_F$ (cm <sup>3</sup> /molecule-s)
1) $O_2(^1\Delta) + O_2(^1\Delta)$	$\rightarrow O_2(^1\Sigma) + O_2(^3\Sigma)$	$9.5 \times 10^{-28} T^{3.8} e^{700/T}$
2) $O_2(^1\Sigma) + H_2O$	$\rightarrow O_2(^1\Delta) + H_2O$ (M)	$6.7 \times 10^{-12}$
3) $O_2(^1\Delta) + O_2(^3\Sigma)$	$\rightarrow O_2(^3\Sigma) + O_2(^3\Sigma)$	$1.6 \times 10^{-18}$
4) $O_2(^1\Delta) + H_2O$	$\rightarrow O_2(^3\Sigma) + H_2O$	$4.0 \times 10^{-18}$
5) $O_2(^1\Delta) + Cl_2$	$\rightarrow O_2(^3\Sigma) + Cl_2$	$6.0 \times 10^{-18}$
6) $O_2(^1\Delta) + He$	$\rightarrow O_2(^3\Sigma) + He$	$8.0 \times 10^{-21}$
7) $I_2(X) + O_2(^1\Sigma)$	$\rightarrow I + I + O_2(^3\Sigma)$	$4.0 \times 10^{-12}$
8) $I_2(X) + O_2(^1\Sigma)$	$\rightarrow I_2(X) + O_2(^3\Sigma)$	$1.6 \times 10^{-11}$
9) $I_2(X) + O_2(^1\Delta)$	$\rightarrow I_2^* + O_2(^3\Sigma)$	$7.0 \times 10^{-15}$
10) $I_2(X) + I^*$	$\rightarrow I_2^* + I$	$3.8 \times 10^{-11}$
11) $I_2^* + O_2(^1\Delta)$	$\rightarrow I + I + O_2(^3\Sigma)$	$3.0 \times 10^{-10}$
12) $I_2^* + O_2(^3\Sigma)$	$\rightarrow I_2(X) + O_2(^3\Sigma)$	$5.0 \times 10^{-11}$
13) $I_2^* + H_2O$	$\rightarrow I_2(X) + H_2O$	$3.0 \times 10^{-10}$
14) $I_2^* + He$	$\rightarrow I_2(X) + He$	$4.0 \times 10^{-12}$
15) $I + O_2(^1\Delta)$	$\rightarrow I^* + O_2(^3\Sigma)$	$4.54 \times 10^{-12} T^{0.5}$ (M)
16) $I^* + O_2(^3\Sigma)$	$\rightarrow I + O_2(^1\Delta)$	$6.14 \times 10^{-12} T^{0.5} e^{-401.4/T}$ (M)
17) $I + O_2(^1\Delta)$	$\rightarrow I + O_2(^3\Sigma)$	$1.0 \times 10^{-15}$
18) $I^* + O_2(^1\Delta)$	$\rightarrow I + O_2(^1\Sigma)$	$4.0 \times 10^{-24} T^{3.8} e^{700/T}$
19) $I^* + O_2(^1\Delta)$	$\rightarrow I + O_2(^3\Sigma)$	$5.0 \times 10^{-14}$
20) $I^* + I$	$\rightarrow I + I$	$1.6 \times 10^{-14}$
21) $I^* + H_2O$	$\rightarrow I + H_2O$	$2.0 \times 10^{-12}$

(M) = Modified from reduced AFWL Mod 1 rate package

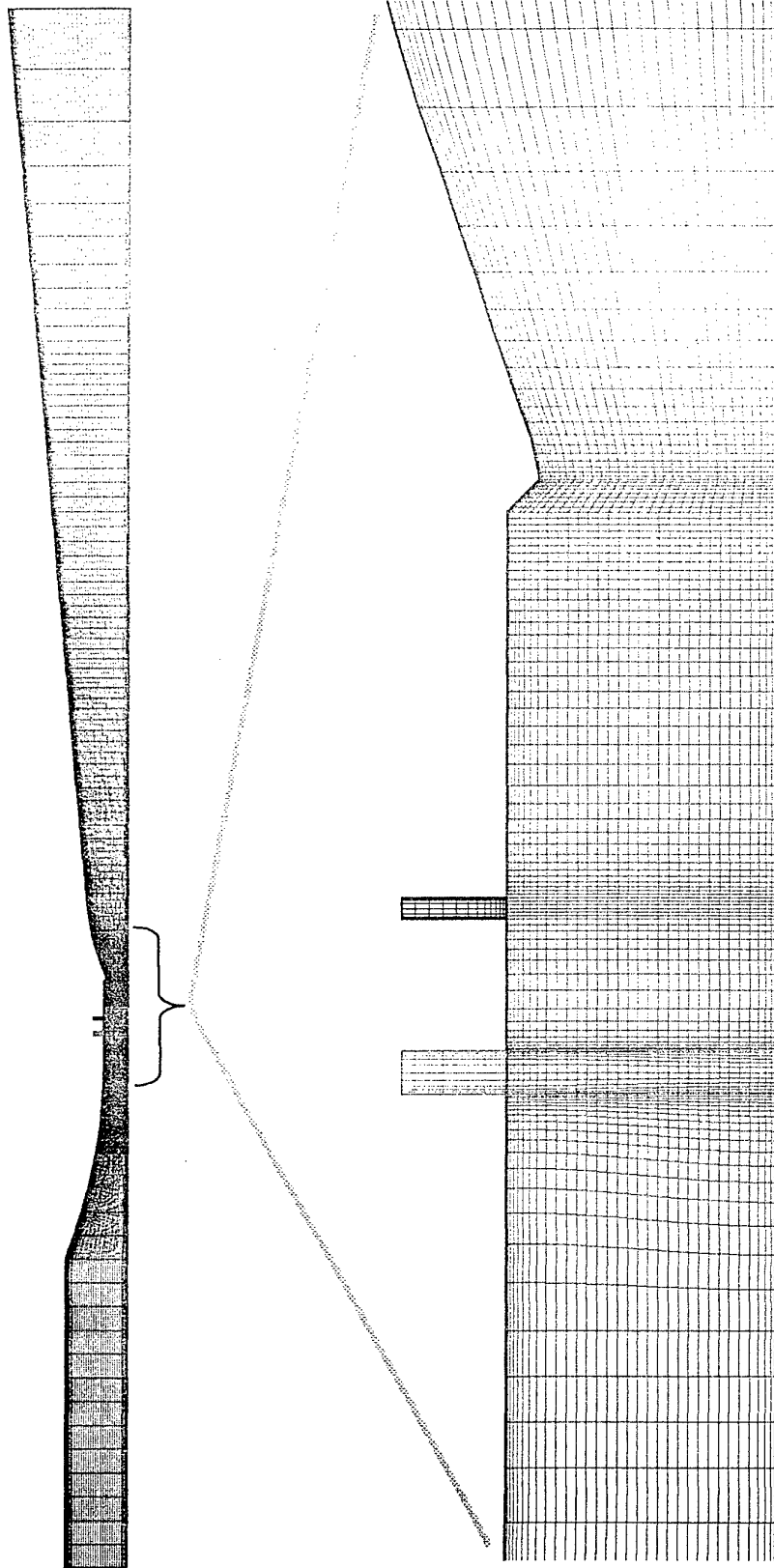


# 3-d MINT RADICL Mesh (Side View)



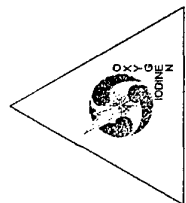
Full Grid (symmetric about centerline)

- 155,000 grid points

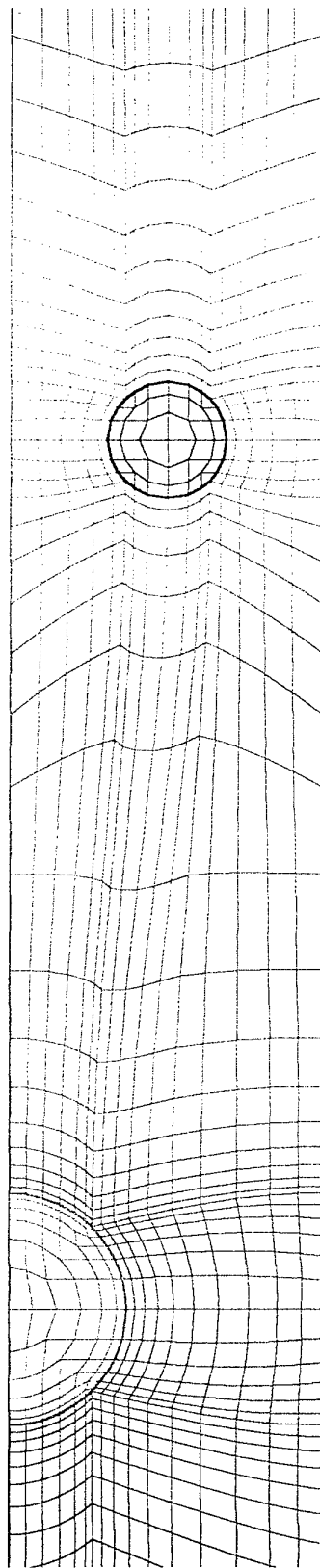




# 3-d MINT RADICL Mesh (Top View)

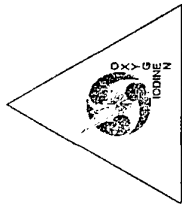


Expanded View in Region  
of Secondary Injection

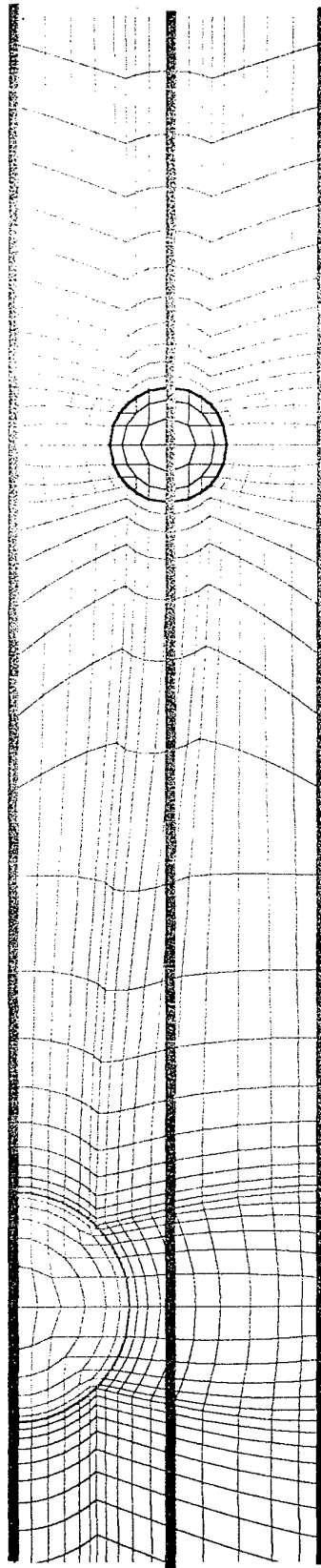




# 3-d MINT RADICL Mesh (Top View)

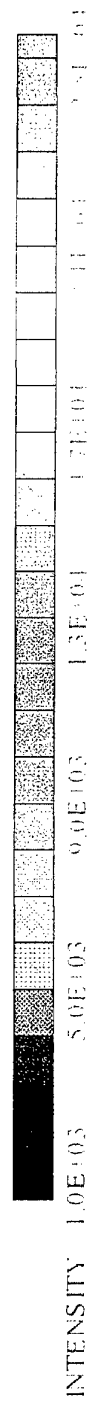
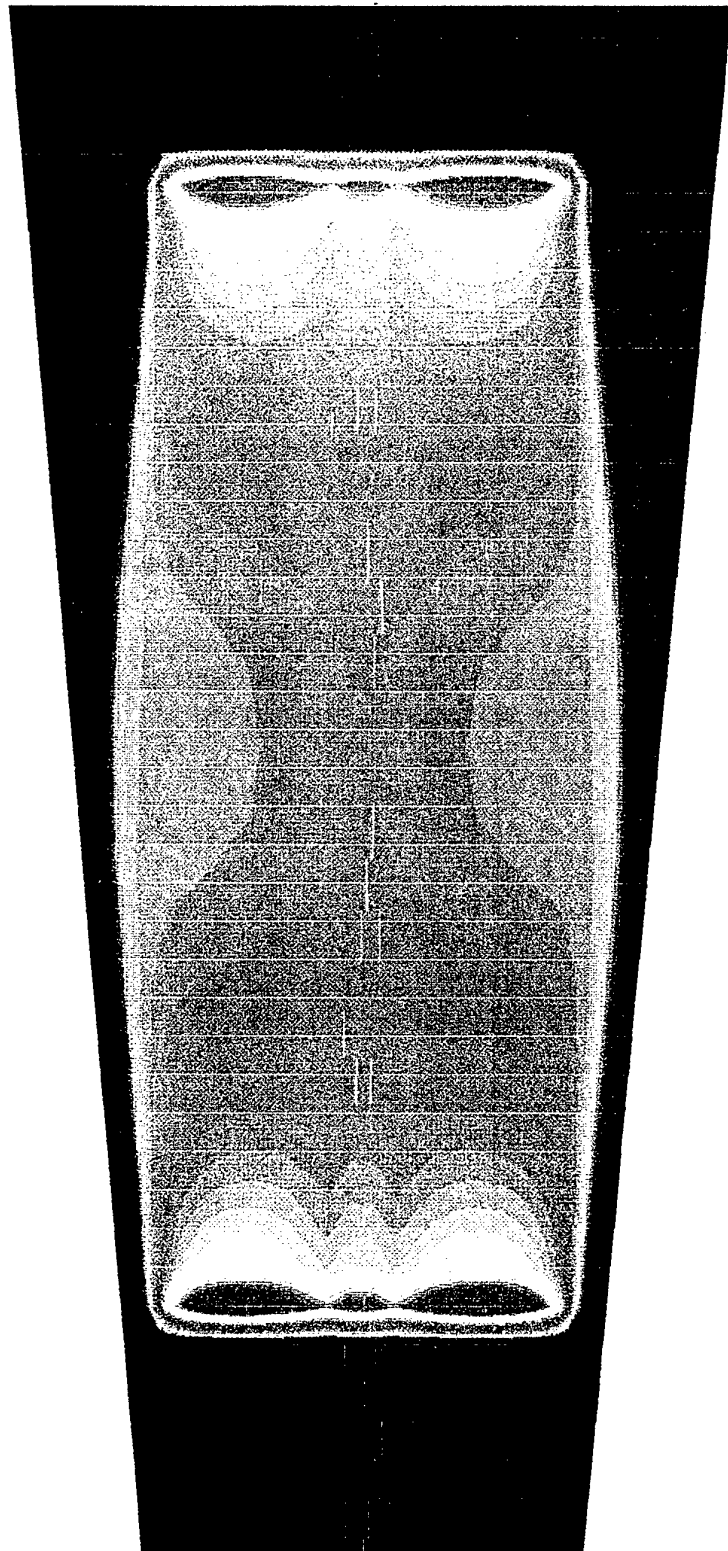
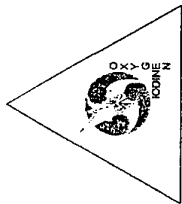


Expanded View in Region  
of Secondary Injection





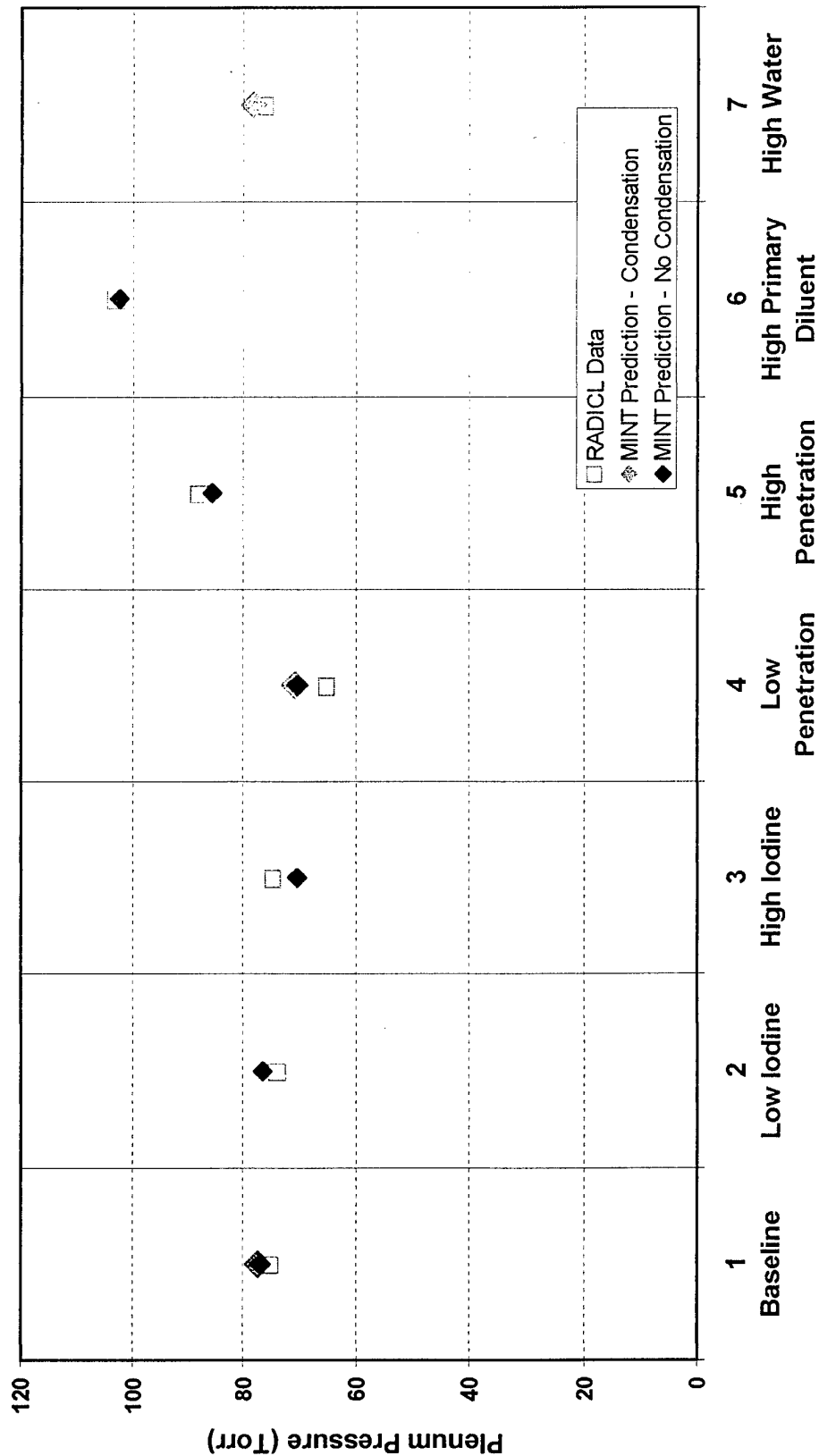
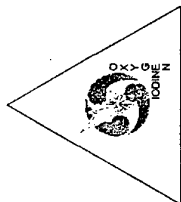
# 3-D MINT RADICL Intensity Profile Case 1 - Baseline (Condensation)





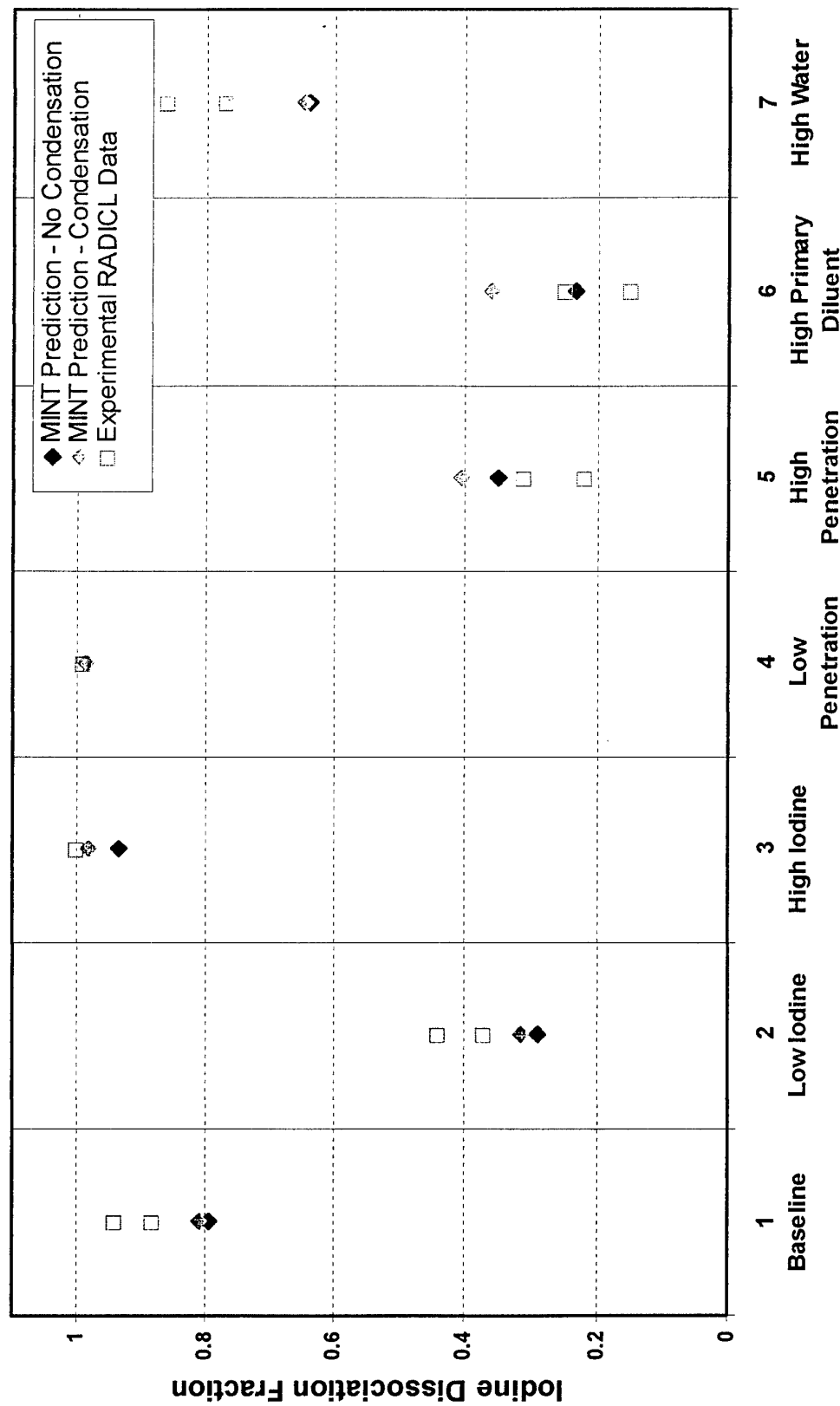
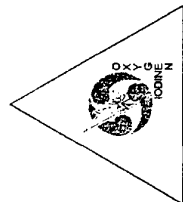


# Comparison of 3-D MINT Plenum Pressure with RADICL 7-Pack Plenum Pressure Data



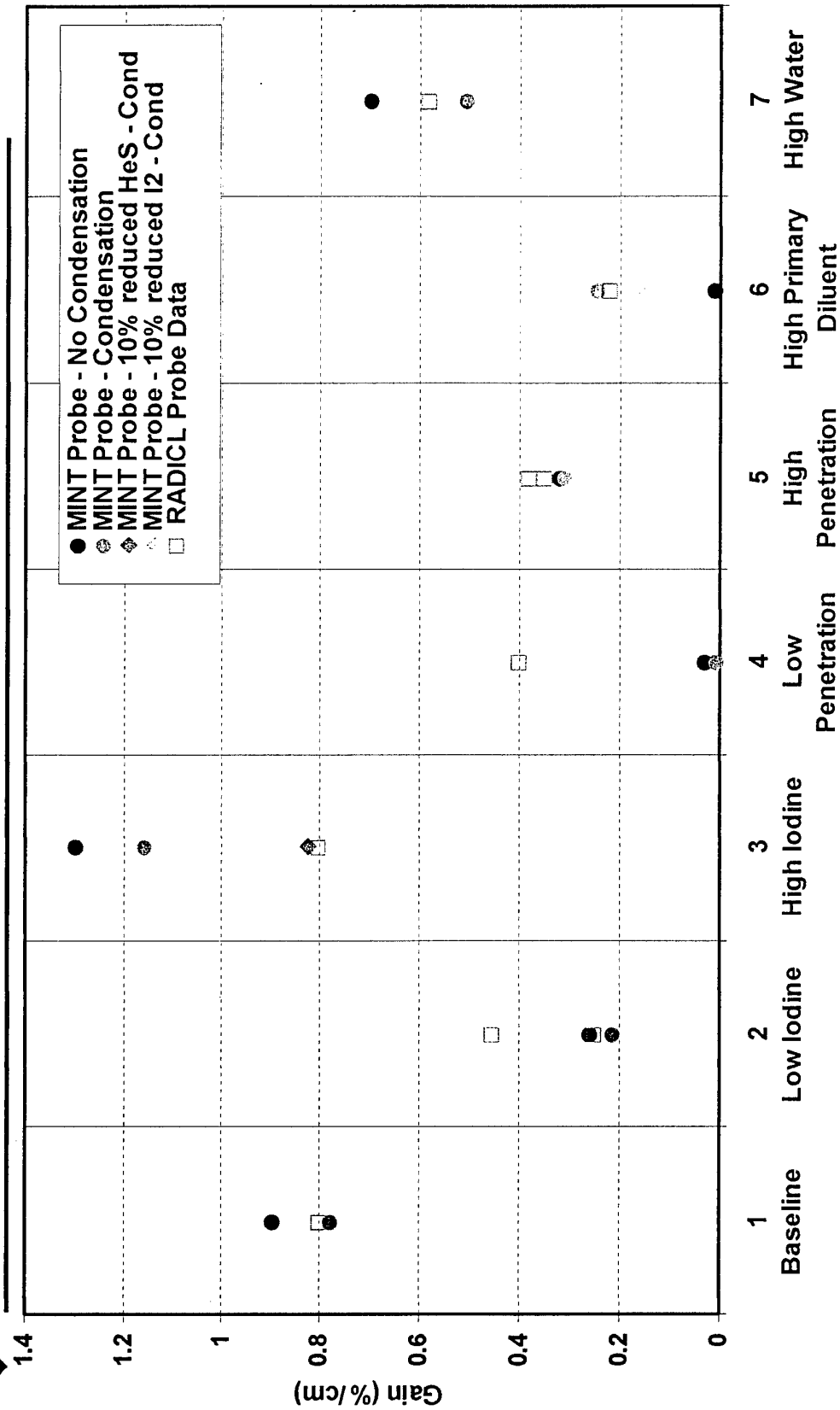
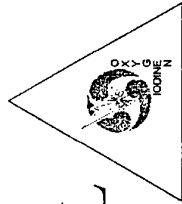


# Comparison of 3-D MINT Avg Dissociation with RADICL 7-Pack Dissociation Data



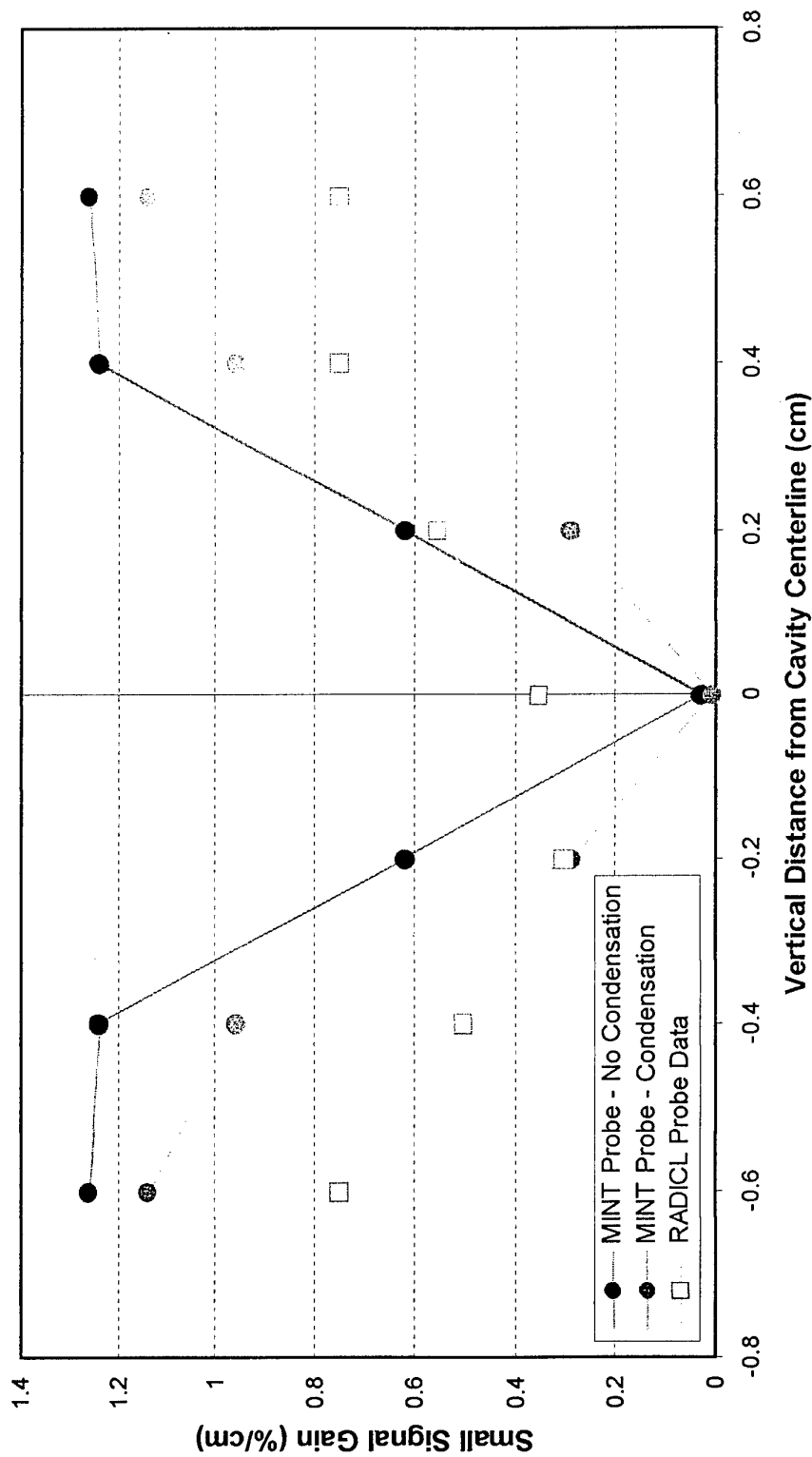
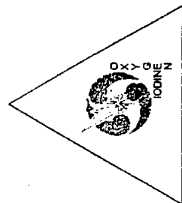


# Comparison of 3-D MINT Probe Gain with RADICL 7-Pack Gain Probe Data



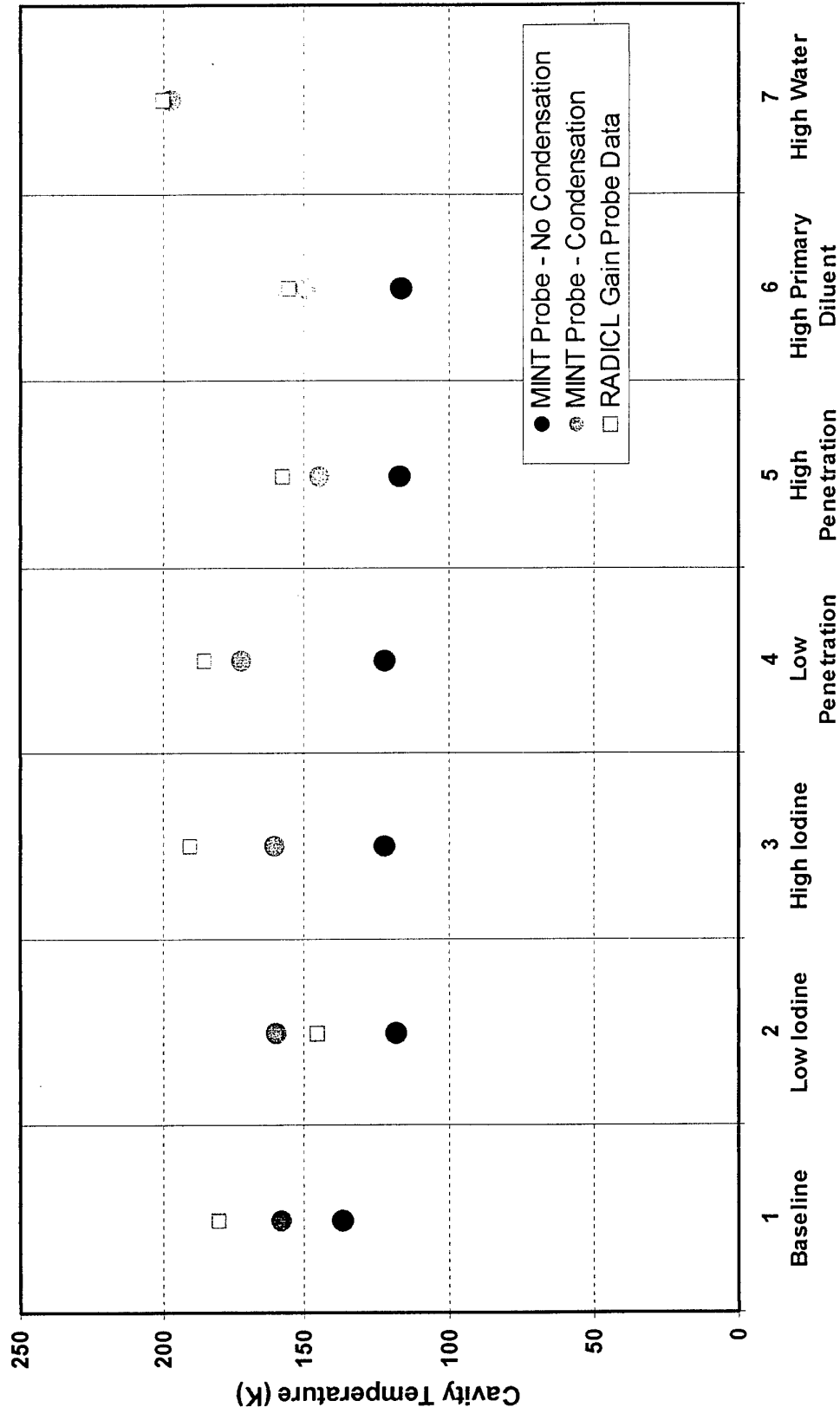
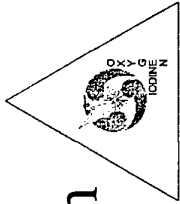


# Vertical Gain Scan Comparison of 3-D MINT Probe Gain Vs RADICL 7-Pack Data (Case 4 - Low Penetration)



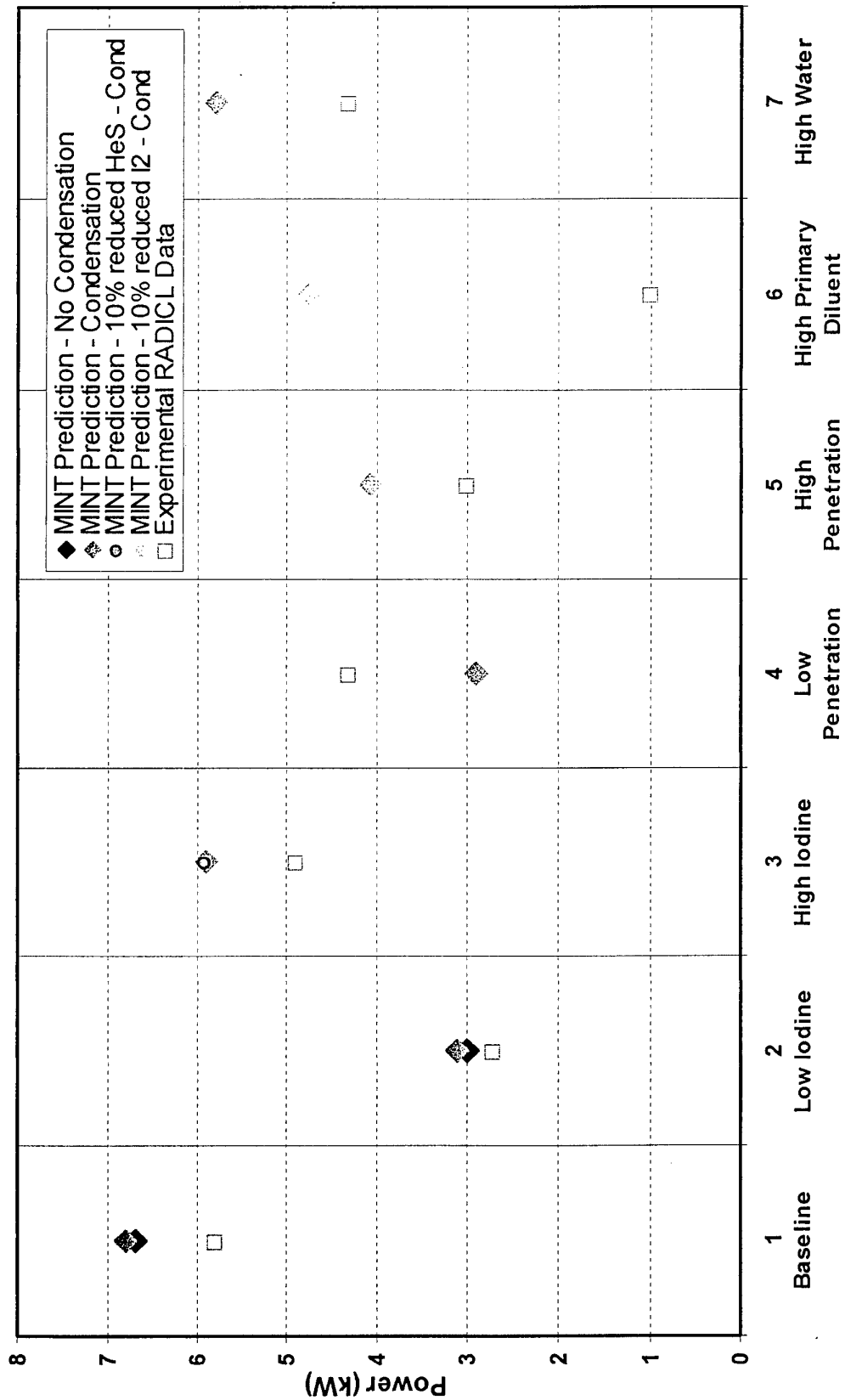
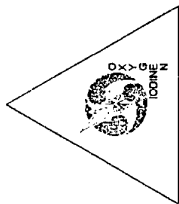


# Comparison of 3-D MINT Cavity Temperature with RADICL 7-Pack Cavity Temperature Data



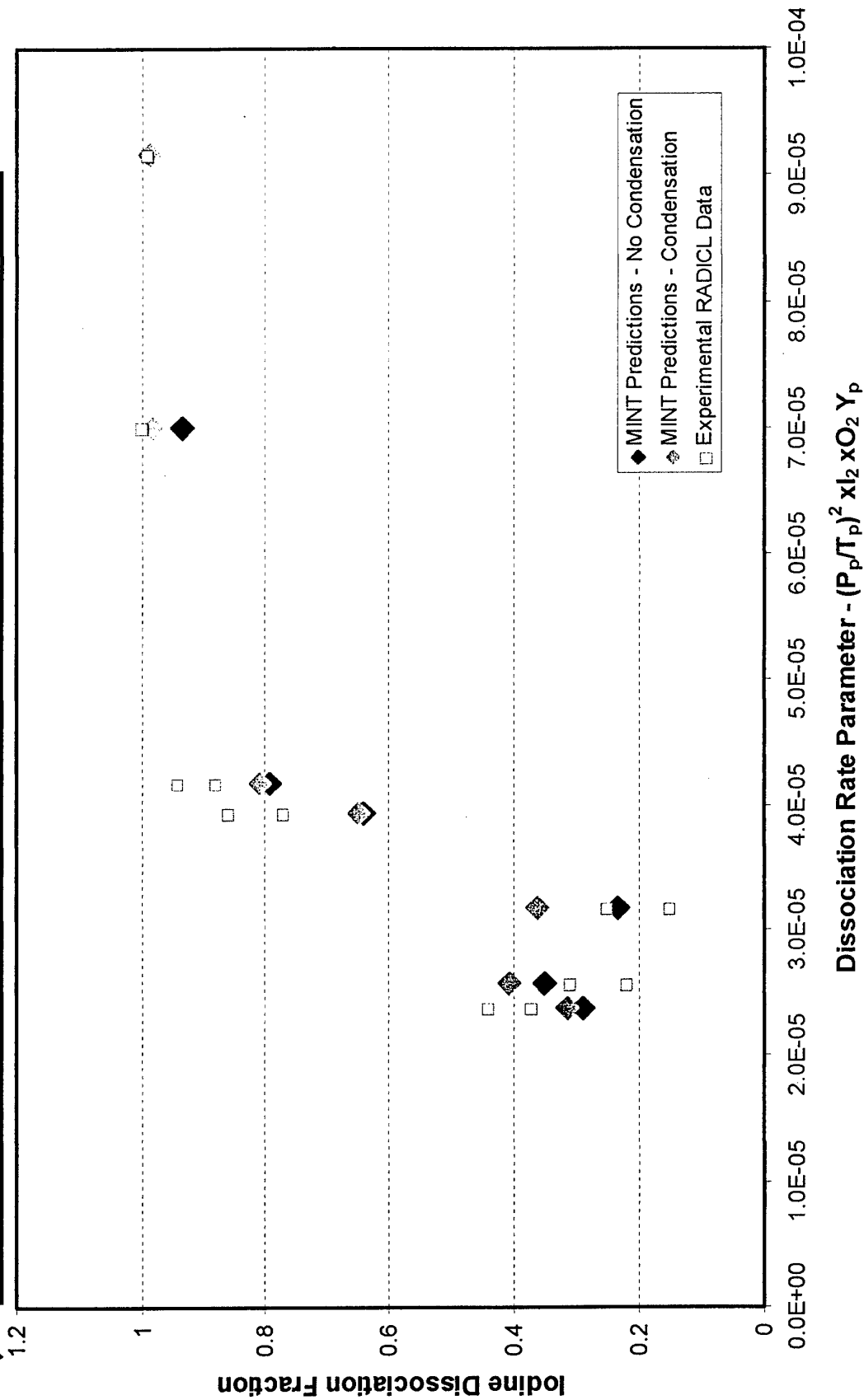
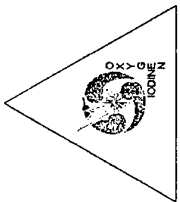


# Comparison of 3-D MINT Power with RADICL 7-Pack Power Data





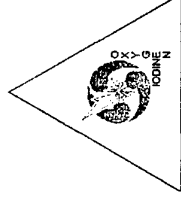
# 3-D MINT RADICL Dissociation Predictions Versus Dissociation Rate Parameter





# MINT Validation Preliminary Summary

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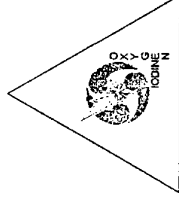
- Very good prediction of experimental gain, dissociation, and cavity temperature TRENDS
- Fair to good prediction of experimental gain MAGNITUDES may mean adjustments in certain kinetic rates
- Water condensation seems to explain cavity temperature measurements
- Power comparisons show good agreement with trend but only fair agreement with magnitude
  - May be kinetics issue with respect to AFRL water quenching kinetics





# Current/Future Work

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- Conducting additional perturbation calculations
- Planning to assess grid resolution and solution accuracy
- Planning to demonstrate parallel MINT speedup on RADICL Case
- Planning to implement recommendations from MINT workshop

**RECENT EXPERIMENTAL RESULTS ON COIL DEVICE  
IN PRAGUE**

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Vít JIRÁSEK, Jan KUŽELKA

Department of Gas Lasers  
Institute of Physics, Academy of Sciences of the Czech Republic

## EXPERIMENTAL

### SSCOIL with JSOG - construction finished a year ago

#### Singlet oxygen generator

made of Plexiglas, cross section of 50 x 48 mm,  
20 cm long BHP jets, 2 chlorine injectors in side walls (10 or 15 cm from top),  
BHP jet injectors - 6 mm plate, 304 - 380 openings of 0.8 mm,  
( $S = 3.2 - 4.0 \text{ cm}^{-1}$ ),  
liquid jets (velocity  $\sim 6 \text{ m s}^{-1}$ ) driven by  $\Delta P$  created by a gear pump.

#### Close-loop BHP system

BHP tank with stainless steel heat exchanger, refrigerator ( $\sim 2 \text{ kW}$ ),  
BHP circulation - gear pump ( $110 \text{ l min}^{-1}$ ),  
Liquiflo comp., model 312, frequency transducer,  
continuous COIL operation at  $40 \text{ mmol Cl}_2/\text{s}$  up to  $\sim 4$  minutes,  
total time of JSOG operation with 15 litres of BHP  $\sim 40 \text{ min}$ .

#### Generator gas outlet and subsonic channel (schema)

- throttle valve for choking the gas flow,
- electro-pneumatically controlled vacuum tight flat valve,
- diagnostic cell:  $\text{O}_2(\Delta_g)$  emission at 1270 nm by Ge photodiode,  
 $\text{O}_2(^1\Sigma_g)$  emission at 762 nm (Si photodiode) for  $c_{\text{H}_2\text{O}}$ ,  
 $\text{Cl}_2$  chlorine concentration measurement from light absorption  
(330 nm),  
gas pressure, temperature
- injector of primary He (2 rows of  $25 \times 0.7 \text{ mm}$  i.d.,  $\pm 45^\circ$ ).

#### Iodine injector (nozzle)

- stainless steel block with inner duct of  $50 \times 9.6 \text{ mm}$ ,
- 2 rows of openings (21 holes 0.8 mm and 42 holes 0.4 mm),
- heated by two transistors up to  $60 - 90^\circ\text{C}$ ,
- a distance between  $\text{I}_2$  injection and the sonic throat adjustable to 6 - 10 mm..

### Supersonic nozzle and optical cavity

- single horizontal slit(critical height 6.7 mm, width 50 mm),
- made of stainless steel (or Plexiglas), inserted into a laser body,
- shape designed according to the method of characteristics and still opened by  $3^\circ$ ,
- distance between the throat and resonator optical axis from 35 to 55 mm,
- resonator 85 cm long, lasing gain region 5 cm,
- multimode output beam 3.7 cm x 1.6 cm.

### Vacuum pumping system

- Roots blower and single-stage rotary pump (RUTA 3001/2, Leybold),  
 $3000 \text{ m}^3 \text{ h}^{-1}$ ,
- $\text{LN}_2$  trap with ribbed heat exchanger.

### Iodine system

**A new system of solid iodine evaporation by preheated He** flowing through iodine bed,

**Advantage** - high area g/s interface for intensive heat transfer from preheated He to  $\text{I}_2 \Rightarrow$  **high  $\text{I}_2$  flow rates at small tank dimensions**,

**Design:** solid iodine in tank made of stainless steel cylinder with a glass liner,  
- He heater upstream of the tank., He temperature up to  $500^\circ\text{C}$  before entering the  $\text{I}_2$  tank

- tank capacity ~30 min operation at  $2 \text{ mmol } \text{I}_2 / \text{s}$ ,
- iodine concentration from light absorption (488 nm,  $\epsilon = 444.6 \text{ l/mol cm}$ , or  $\sigma_{488} = 1.7 \times 10^{-18} \text{ cm}^2$ ),
- spectral photometer Spekol 11 with fibre optics,
- $\text{I}_2$  diagnostic cell: pressure and temperature sensing,
- $\text{I}_2$  flow rate from He flow rate,  $\text{I}_2$  concentration, P and T in diagnostic cell,
- additional He through a line by-passing the iodine tank, enables to adjust required  $\text{I}_2$  flow rate (automatic control is prepared).

## **Data acquisition system**

Most of the measured parameters processed by A/D converter (32 channels) and by PC

## **TESTS OF COIL SUBSYSTEMS**

### **Tests of jet SOG**

#### **Experiments with $\text{He}_{\text{prim}}$ introduced downstream of the generator**

Values  $P_{\text{gen}} \Rightarrow \text{O}_2(^1\Delta_g)$  yield easily controlled by choking exiting gas - **Fig. 1a.**,

P in subsonic channel: 3.2 - 3.9 kPa (24 – 29 torr),

$\text{O}_2(^1\Delta_g)$  yield - **Fig. 1b**

water vapour pressure - **Fig.1c**

gas temperature in subsonic channel - **Fig.1c**

#### **Experiments with $\text{He}_{\text{prim}}$ admixed into $\text{Cl}_2$ upstream of the generator**

$P_{\text{gen}}$  on throttle valve position - **Fig. 2a**

$\text{O}_2(^1\Delta_g)$  yield - **Fig. 2b**

gas temperature in subsonic channel - **Fig. 2c, 3**

Effect of SOG run time on BHP temperature (40 mmol  $\text{Cl}_2$ /s + 80 mmol  $\text{He}_{\text{prim}}$ /s,

15 l BHP):  $dT/dt = 5^\circ\text{C}/\text{min}$  - **Fig. 3,**

BHP jets temperature by 2 – 4°C higher than bulk temperature,

## Tests of gas dynamic conditions in COIL device

Tests at "cold flow run":

**The average Mach number,  $M_1$ , in the subsonic channel<sup>1</sup>**

$$n = (\kappa / R \mu)^{1/2} (A P_{\text{stat}} / T^{*1/2}) M \{1 + M^2(\kappa - 1) / 2\}^{1/2}$$

$n$  - total molar flow rate,  $\kappa$  - adiabatic constant,  $R$  - gas constant,  $\mu$  - molecular weight,  $A$  - flow cross section,  $P_{\text{stat}}$  - static pressure,  $T^*$  - stagnation temperature.

**Experimental conditions:**

$$\begin{aligned} n_{\text{N}_2} &= 22.3 \text{ mmol/s}, & n_{\text{He}} &= 89.5 \text{ mmol/s}, \\ P_{\text{sub. ch.}} &= 2055 \text{ Pa}, & A &= 9,5 \times 50 \text{ mm}, \\ T^* &= 293 \text{ K}, \end{aligned}$$

Resulting average Mach number:  $M_1 = 0.41$ .

**Average Mach number in the resonator optical axis:  $M_2 = 1.9 - 1.4$**

**Local Mach number in the centreline of ss cavity:**

$$P_{\text{stat}} / P_{\text{Pit}} = \{2 / [(\kappa - 1) M_2^2]\}^{\kappa/(\kappa-1)} \{[2 M_2^2 \kappa / (\kappa + 1)] - [(\kappa - 1) / (\kappa + 1)]\}^{1/(\kappa-1)}$$

$P_{\text{Pit}}$  - Pitot tube pressure,  $A = 9.16 \cdot 10^{-4} \text{ m}^2$ ,  $h = 16 \text{ mm}$ ,  $w = 55 \text{ mm}$ .

**Local Mach number in the resonator optical axis:  $M_2 = 2.4 - 2.2$**

## Tests of iodine vaporiser

- **study of I<sub>2</sub> flow rate**: controlled by He temperature, He flow rate, voltage and time of tank jacket heating.

**Time dependence of I<sub>2</sub> flowrate** - **Fig. 4** (preheated tank, without He heating),  
**Fig. 5** (effect of He temperature),

⇒ **preheating of secondary gas can compensate the negative effect of iodine cooling** caused by evaporation heat,

- **iodine evaporation system with preheated gas can provide constant I<sub>2</sub> flow**

## Mixing of primary (O<sub>2</sub> + He) and secondary (I<sub>2</sub> + He) flow

Iodine jet penetration given by **penetration parameter**<sup>3</sup>

$$\Pi = n_s / n_p \{ (M_s T_s P_p / M_p T_p P_s) \}^{1/2}$$

**Experiment** : at  $P_{out} = 370 - 430$  W:

primary flow: 37 mmol O<sub>2</sub>/s + 1 mmol Cl<sub>2</sub>/s + 80 mmol He/s

$n_p = 118$  mmol/s,  $M_p = 13,35 \times 10^{-3}$  kg/mol,

$T_p = 273$  K,  $P_p = 3800$  Pa,

secondary flow: 40 mmol He/s + 1.1 mmol I<sub>2</sub>/s

$n_s = 41.1$  mmol/s,  $M_s = 10.7 \times 10^{-3}$  kg/mol

$T_s = 343$  K,  $P_s = 13500$  Pa

Resulting **penetration factor**:  $\Pi = 0.093$ ,

A hardware design parameters ⇒ **full penetration parameter**,  $\Pi_{full}$ <sup>3</sup>:

$$\Pi_{full} = d A_s / 5 D A_p$$

d - height of subsonic channel, D - diameter of iodine injector opening,

$A_s$  - cross-section of secondary flow,  $A_p$  - cross-section of primary flow.

Our COIL:  $\Pi_{full} = 0.105$ ,

$\Pi/\Pi_{full} = 89 \%$

## Experiments with laser generation

**Main problem: entraining of BHP droplets and BHP foam into gas channel**

- geometry of the generator near the gas outlet (extremely high gas velocity of gas crossing last rows of jets) - effect increases with increasing generator cross section,

- problems of liquid film creeping up the walls

**Typical experimental conditions:**

40 mmol  $Cl_2/s$ , 80 mmol  $He_{prim}/s$ , 40 mmol  $He_{sec}/s$ , 0 - 3.0 mmol  $I_2/s$ ,

$x = 6$  mm or 10 mm (distance between the  $I_2$  injector and nozzle throat),

$\delta_e = 0.85 - 2.6 \%$  (resonator mirrors output coupling),

$l = 35$  or 55 mm (distance between the critical section and optical axis)

## Experiments with prim. He downstream JSOG (behind throttle valve)

An output power 60 W - 150 W at  $I_2$  flow rate of 0.5 - 1.25 mmol/s and

$\delta_e = 0.85 - 2.6 \%$ . Effects of the distance  $I_2$  injector - nozzle throat, and nozzle throat - opt. axis - not revealed in this series for poor reproducibility for escaping liquid problems.



## Primary He admixed into Cl<sub>2</sub> upstream of the generator

### Earlier experimental series

**P<sub>L</sub> better** (to 280 W) for shorter distance I<sub>2</sub> injector - nozzle throat (5 mm)

- result of **smaller loss of I<sup>\*</sup> before nozzle throat**.

Study of effects of **P<sub>gen</sub>, n<sub>I2</sub>, n<sub>He,sec</sub>, δ<sub>e</sub>** and operation time:

- **greater opening of the throttle valve resulting in lower generator pressure** (below 6 kPa ~ 45 torr) **reduced laser power substantially** (in contradiction to a higher O<sub>2</sub>(<sup>1</sup>Δ) yield) - Fig. 6

- **reason: light scattering in the laser active zone on streaming liquid droplets**,

- water concentration was rather low (40 - 50 Pa vs. 580 Pa of O<sub>2</sub>(<sup>1</sup>Δ)),

- effect caused by a lower P<sub>gen</sub> and **higher gas velocity in the generator** (at more opened TV) and **increasing capture of liquid droplets by gas**.

### Later experimental series

**Suppression of escaping liquid increased the laser output power up to 430 W** (38 mmol Cl<sub>2</sub>/s, η<sub>chem</sub> = 12.5 %)

**Laser power - mostly affected by iodine flow rate - Fig. 7**

(P<sub>L</sub> between 375 W and 425 W, if n<sub>I2</sub> between 1.0 and 1.75 mmol/s),

From this time dependence ⇒ **laser power vs. iodine flowrate - Fig. 8**

**Effects of n<sub>I2</sub> on laser power at different output coupling - Fig. 9.**

From this dependence - the **small signal gain and saturation intensity**.

The Rigrod gain saturation model<sup>4</sup>

$$P_w = s \delta_e \{ [ 2 \alpha_{34} l_g / (\delta_e + \delta_o) ]^2 - 1 \} I_s$$

s is the output beam cross-section, δ<sub>e</sub> - total external coupling, δ<sub>o</sub> - internal cavity losses.

Our COIL:  $s = 6.1 \text{ cm}^2$ ,  $l_g = 5.5 \text{ cm}$ , and  $\delta_o = 0.12$

$n_{I2}, \text{ mmol s}^{-1}$	$\alpha_{34}, \text{ cm}^{-1}$	$I_s, \text{ W cm}^2$
0.5	0.0137	3025
1.0	0.0163	3238
1.5	0.0155	4428

**Very important effect of mirrors quality** - a relatively stable  $P_L$  observed with some mirrors only (e.g. **Fig. 6**).

- often a **time decrease in  $P_L$**  caused by **worse quality mirrors** ( **Fig. 10**),

Multimode **beam patterns** - see example

**Comparison of our COIL (jet SOG-COIL) with VertiCOIL (disk SOG-COIL)**  
 from USAF Research Laboratory (data taken from Phipps *et al*<sup>6</sup> and Helms *al*<sup>7</sup>)

	<b>VertiCOIL in AFRL</b>	<b>JetSOG-COIL in IP</b>
Total power	420 W	430 W
Chlorine flow rate	36 mmol/s	37.8 mmole/s
Primary He diluent	135 mmol/s	80 mmol/s
Generator pressure	38 torr	8 kPa (60 torr)
Diagnostic duct pressure	28 torr	3.8 kPa (28.5 torr)
Laser cavity pressure	4.5 torr	380 Pa (2.8 torr)
BHP inlet temperature	-30°C	-22°C
BHP outlet temperature	-19°C	-18°C
Diagnostic duct temp.	-10°C	+2°C
Penetration factor, $\Pi$	0.110	0.093
Full penetrat. factor, $\Pi_{full}$	-	0.105
Chemical efficiency	0.12	0.12
$I_2/O_2$	0.017	0.029
Starting BHP molarity	7.2 M $HO_2^-$ /0.5 M $H_2O_2$	6.7 M $HO_2^-$ /2.3M $H_2O_2$
$O_2(^1\Delta_g)$ yield	0.54 (assumed)	0.72
Mirror reflectivities	0.997/0.982	0.9995/0.981
Mirror scattering loss	0.0025/0.0025	not estimated
Mirror absorption loss	$10^{-5}/10^{-5}$	not estimated
Mode length	3.2 cm	3.7 cm
Gas velocity in cavity	$1.0 \times 10^5$ cm/s	$0.9 \times 10^5$ cm/s
Small signal gain	$0.014 \text{ cm}^{-1}$	$0.015 \text{ cm}^{-1}$
Saturation intensity	-	4 kW $\text{cm}^{-2}$

## CONCLUSIONS

### Experiments with COIL subsystems:

- our designed jet SOG able to generate  $O_2(^1\Delta_g)$  with high excitation efficiency and low water content,
- tests of gas dynamic conditions proved a fast flow in the subsonic channel and supersonic flow in laser cavity,
- originally designed iodine vaporiser using pre-heated He may provide constant iodine flow rates up to 3 mmol/s.

### COIL results:

- proved very detrimental effect of liquid droplets in the laser cavity and called for improvements, which resulted in suppression of liquid droplet escaping from JSOG,
- found optimum experimental conditions suppressing this effect,
- achieved appropriate  $P_L$  and estimated small signal gain and  $I_s$ .

### Near plans:

- to improve COIL parameters (measurements at higher  $n_{Cl_2}$ , using mirrors of better quality and greater aperture, to shorten subsonic channel)

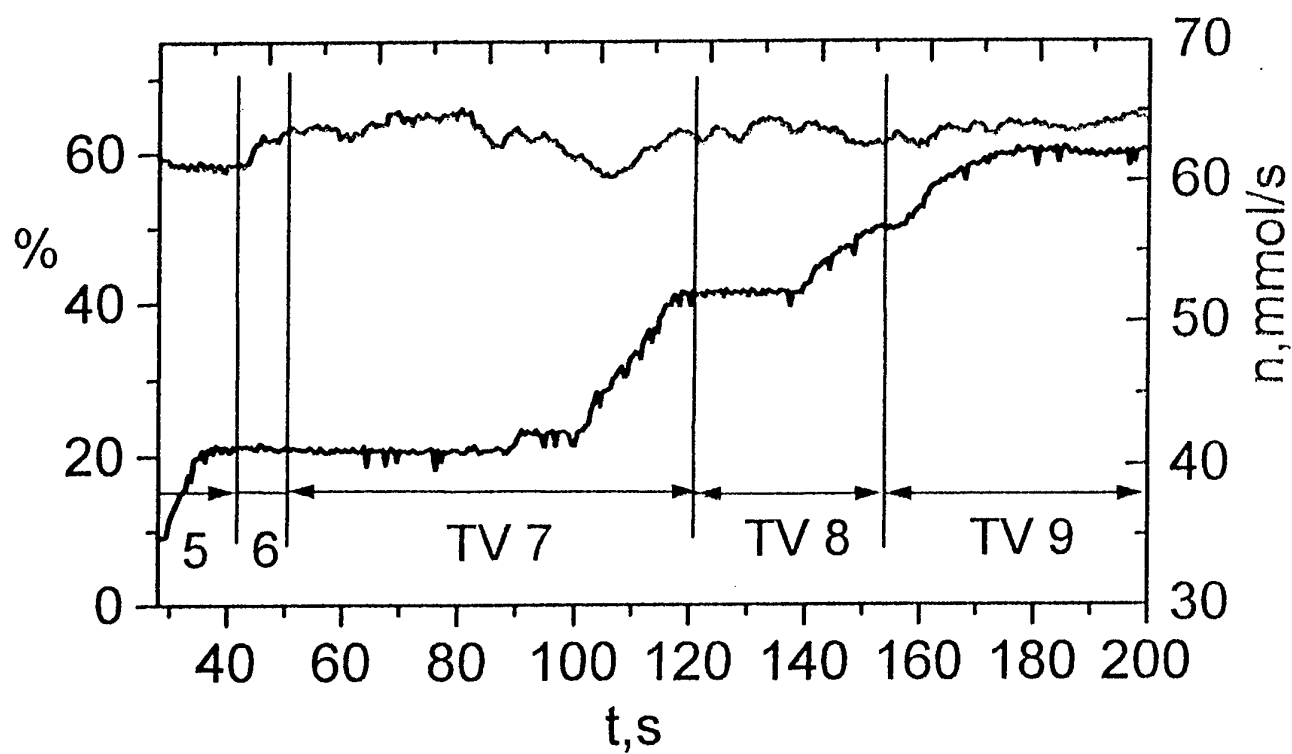
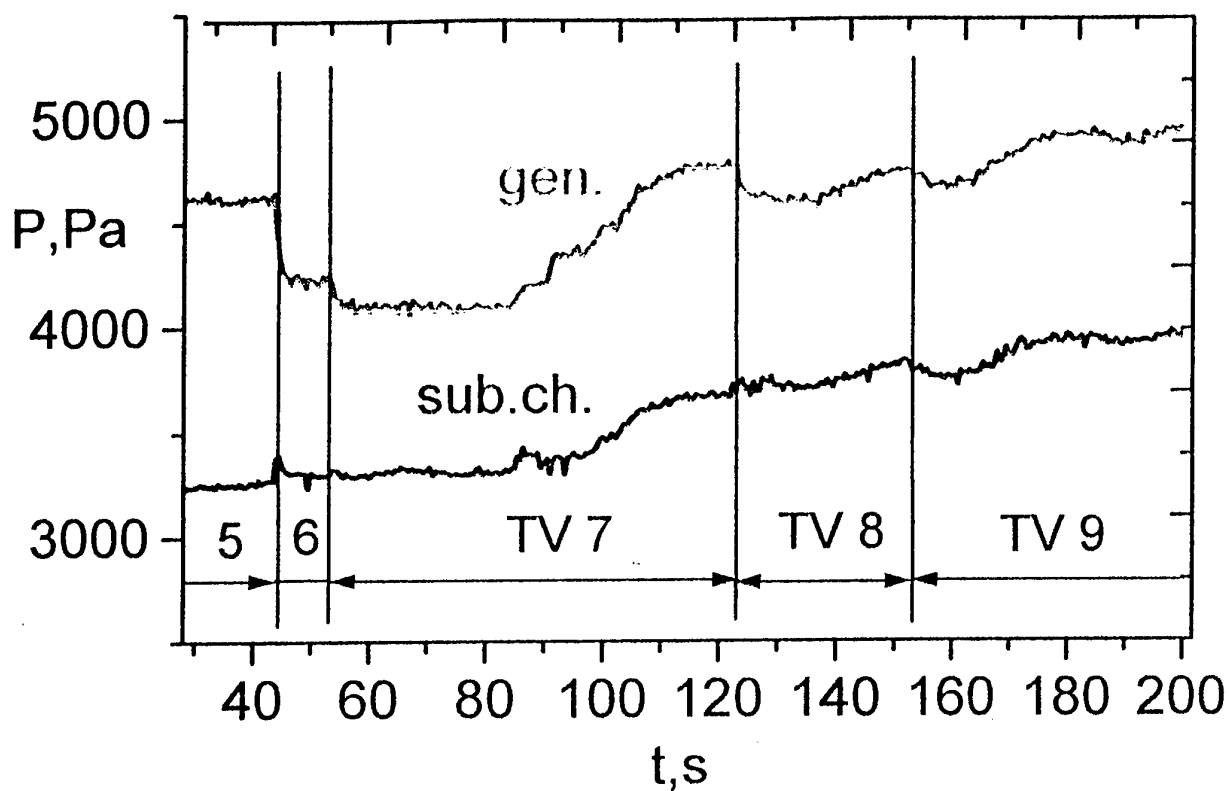


Fig.1a,b : Generator and subsonic pressure,  
 $O_2(^1\Delta)$  yield and chlorine flowrate on time

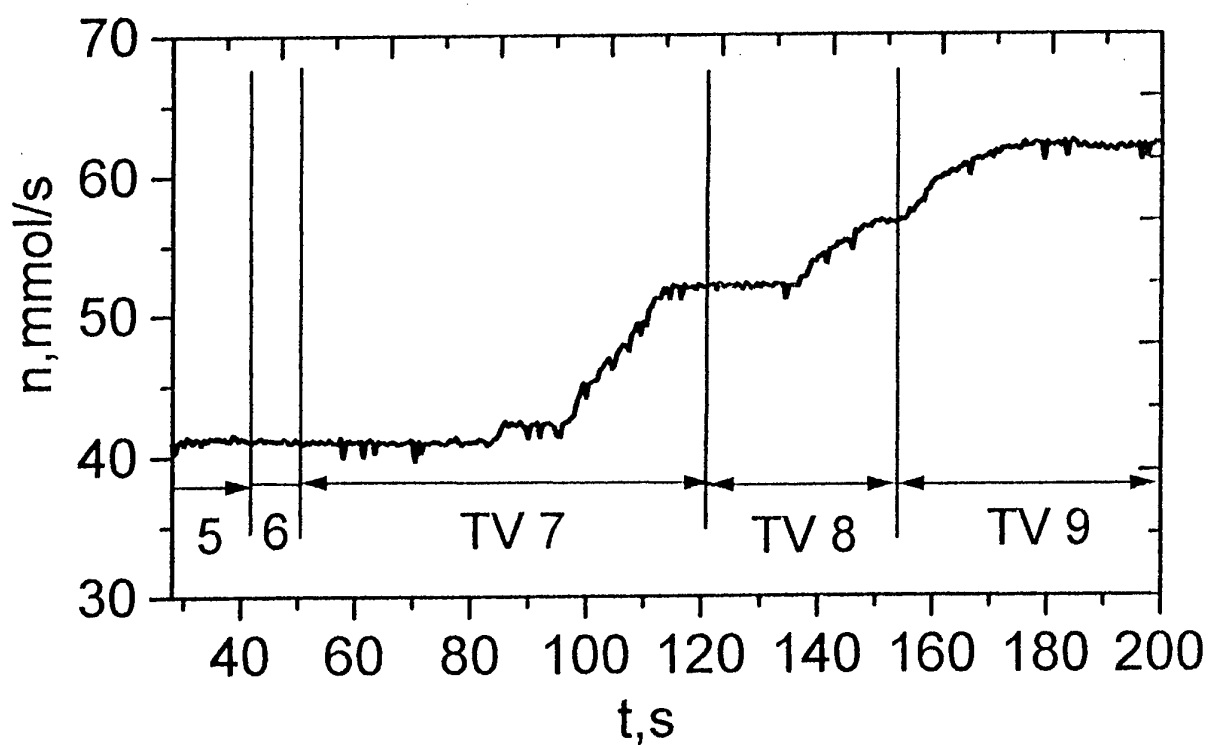
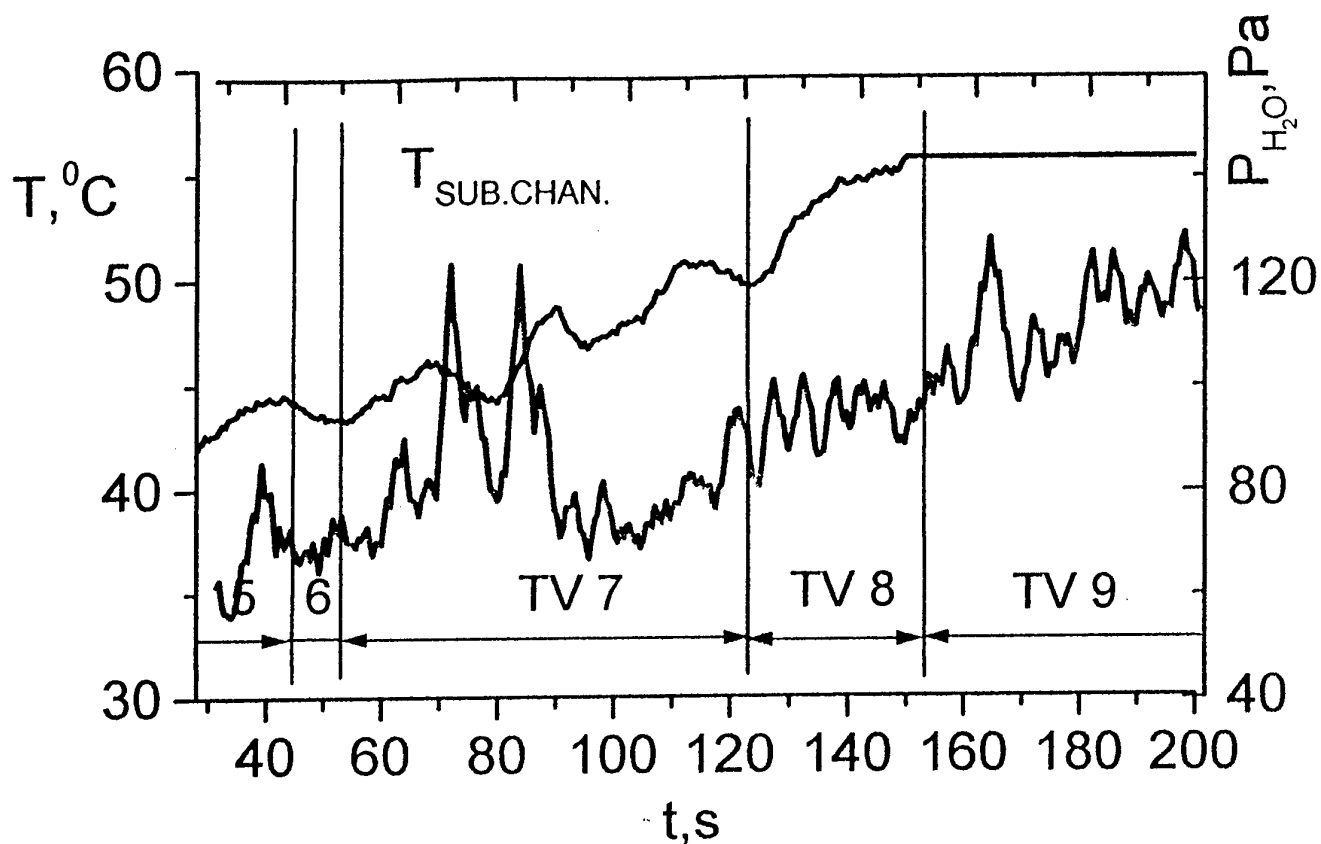


Fig.1c,d : Subsonic channel temperature, water vapor pressure and chlorine flowrate on time

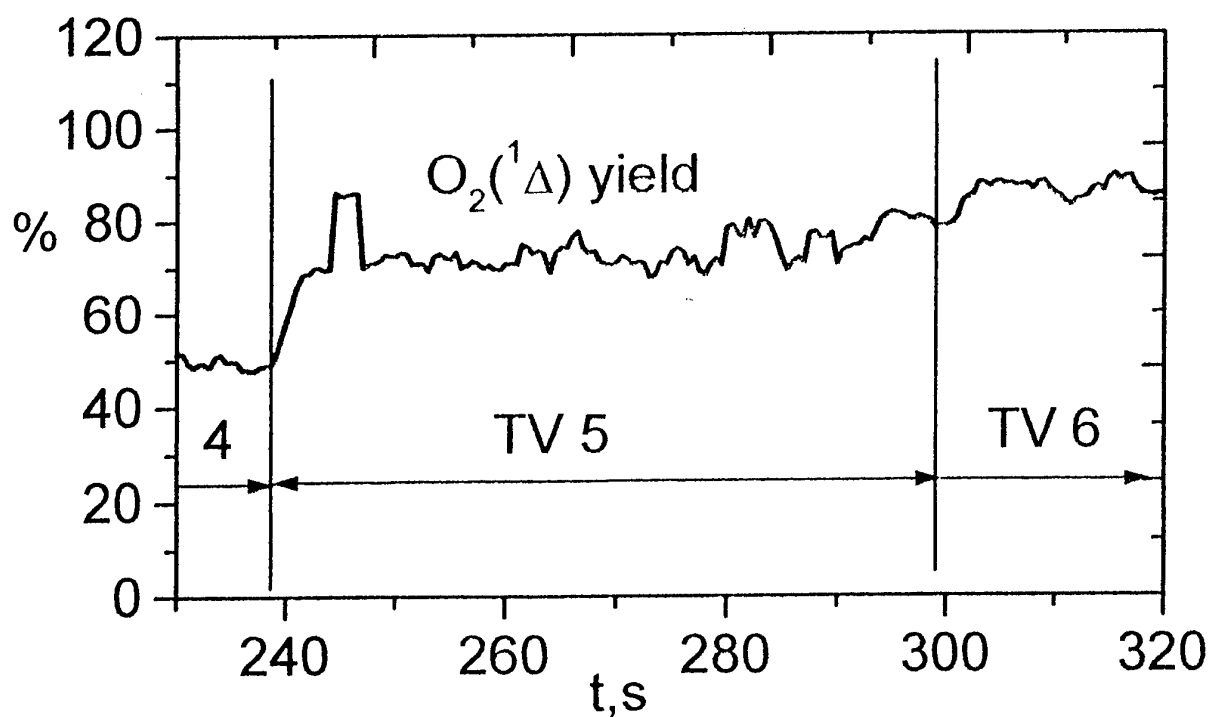
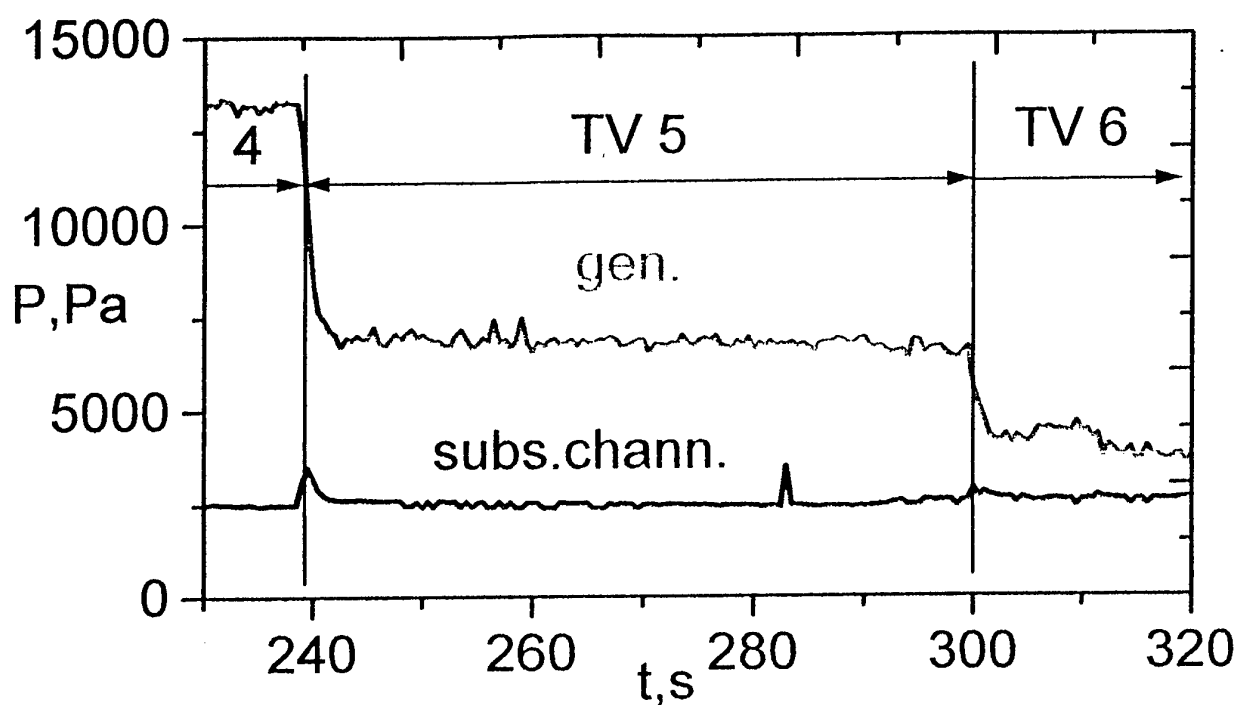


Fig.2a,b : Generator and subsonic channel pressure and  $O_2(^1\Delta)$  yield on time (prim.He into chlorine)

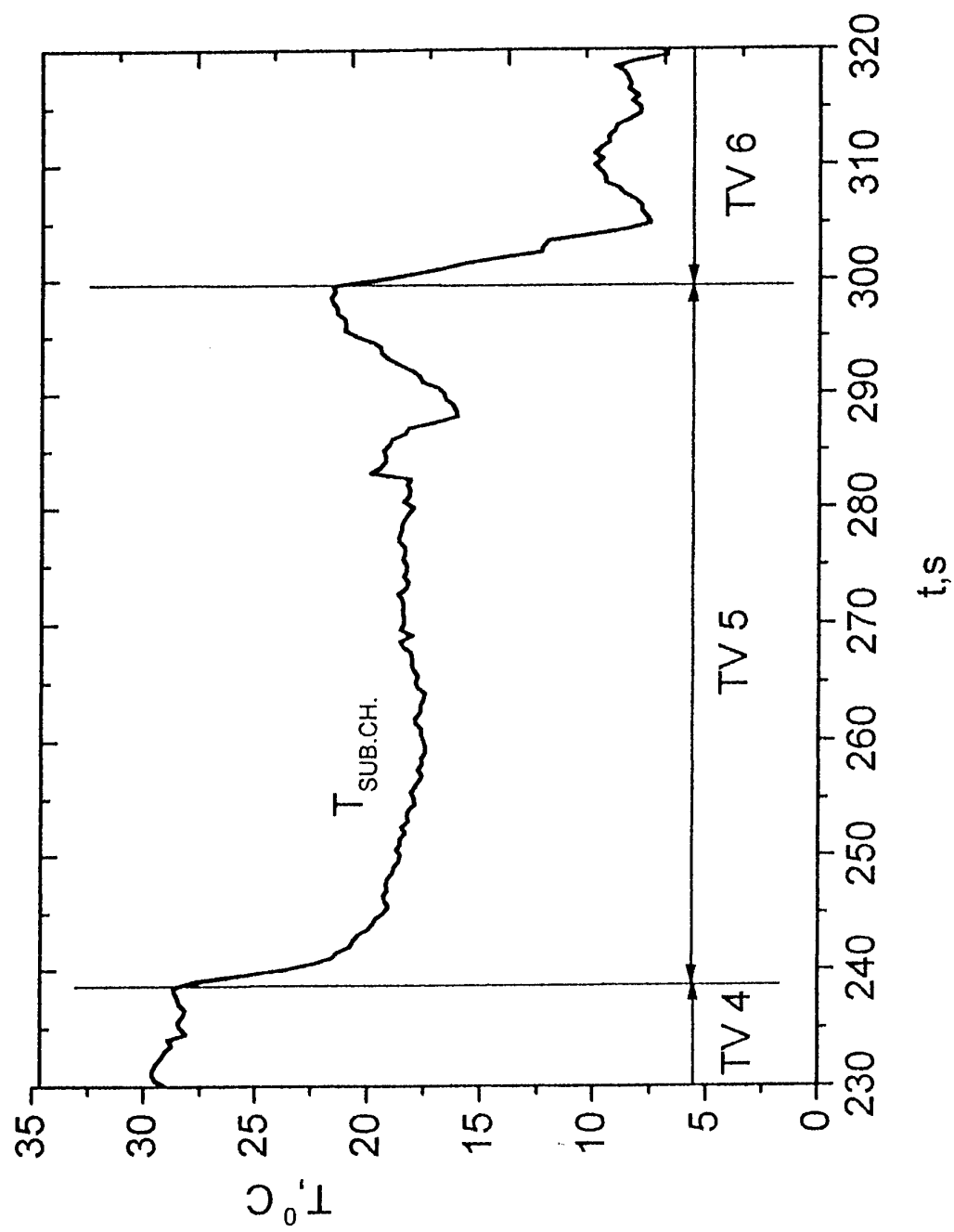


Fig.2c: Subsonic channel temperature on time  
(40 mmol/s  $\text{Cl}_2$ , prim.He into chlorine)



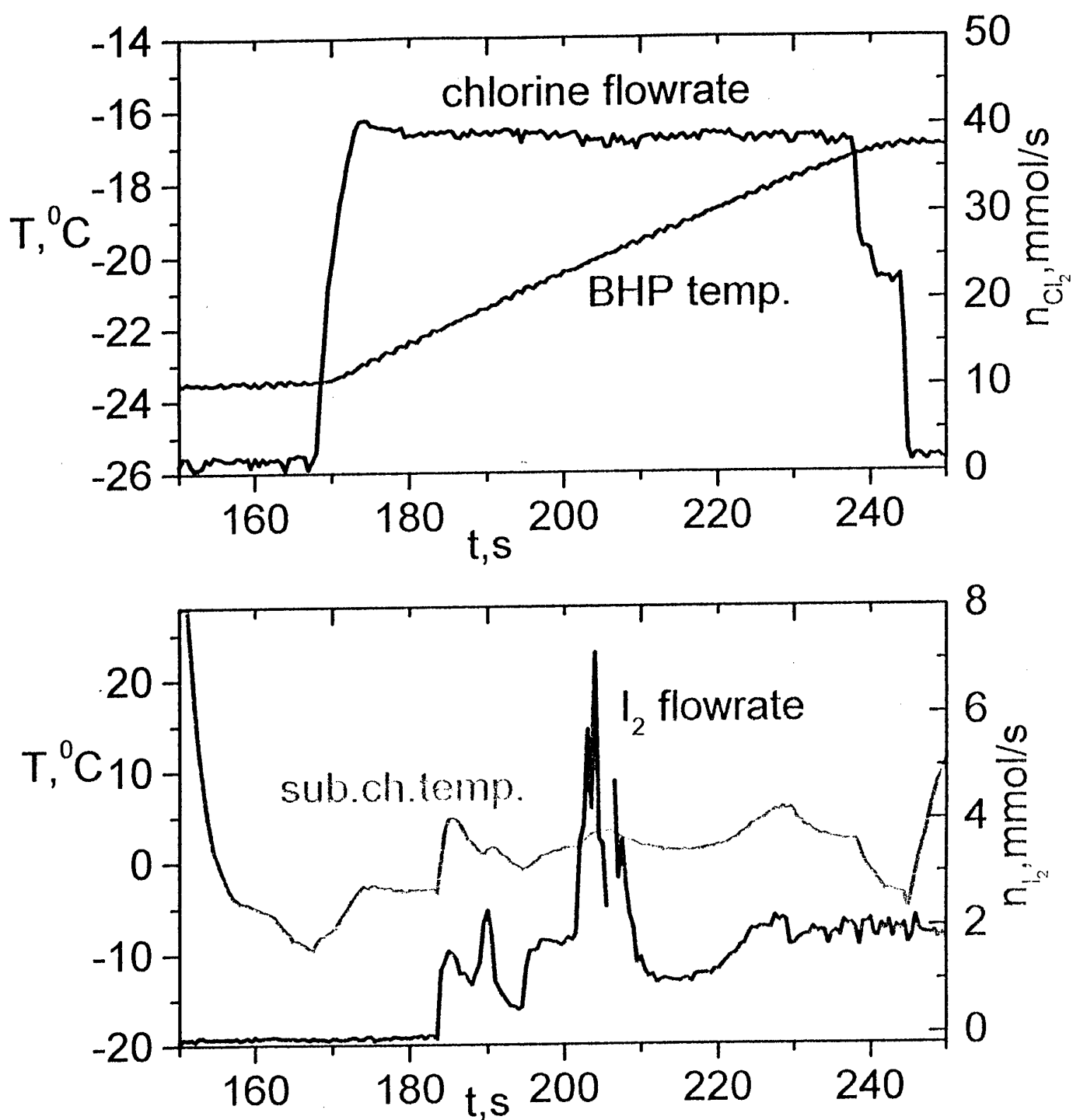


Fig.3. Time dependence of BHP and subsonic channel temperature

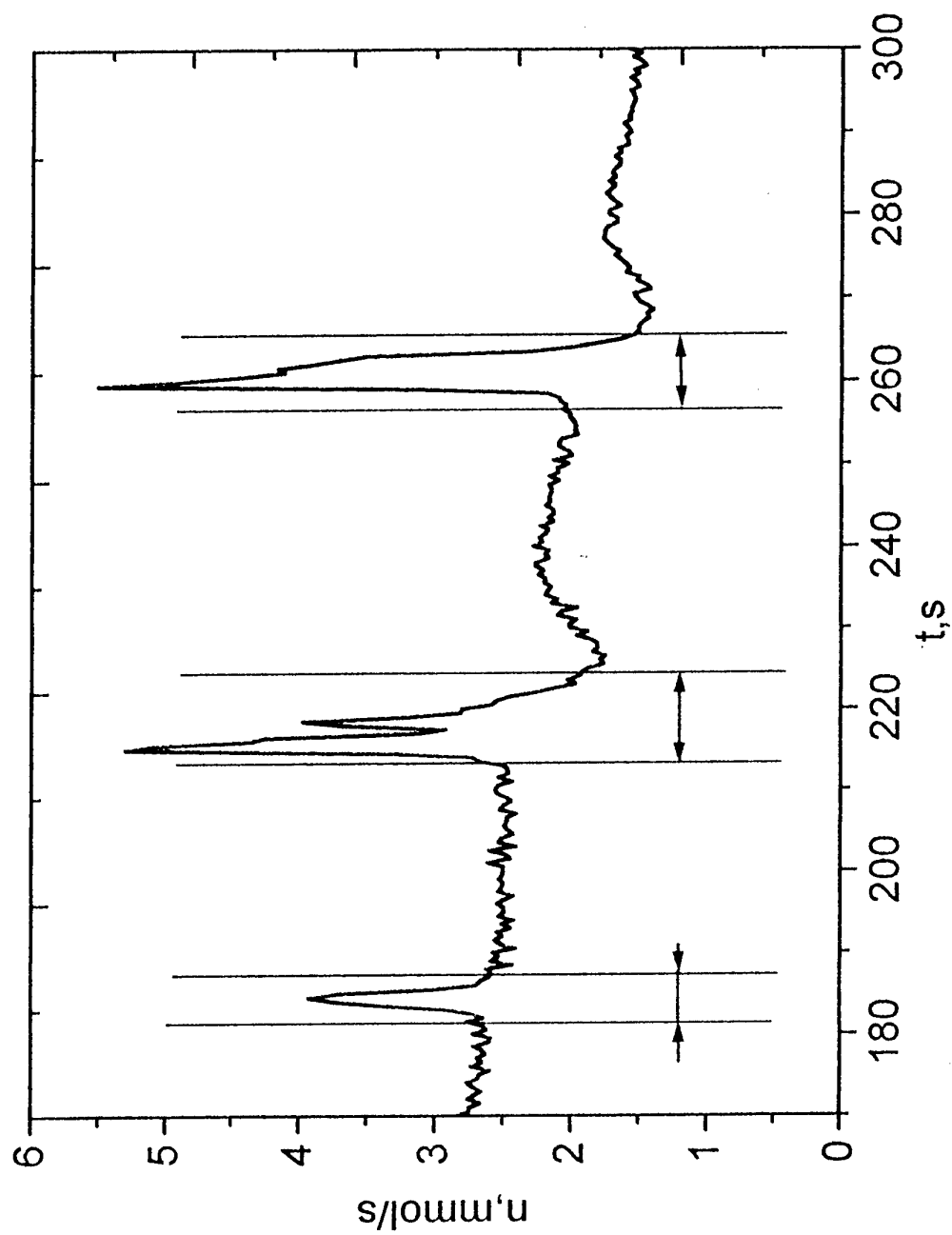


Fig.4: Plot of  $I_2$  flowrate on time  
(in regions between arrows higher flowrates tested)

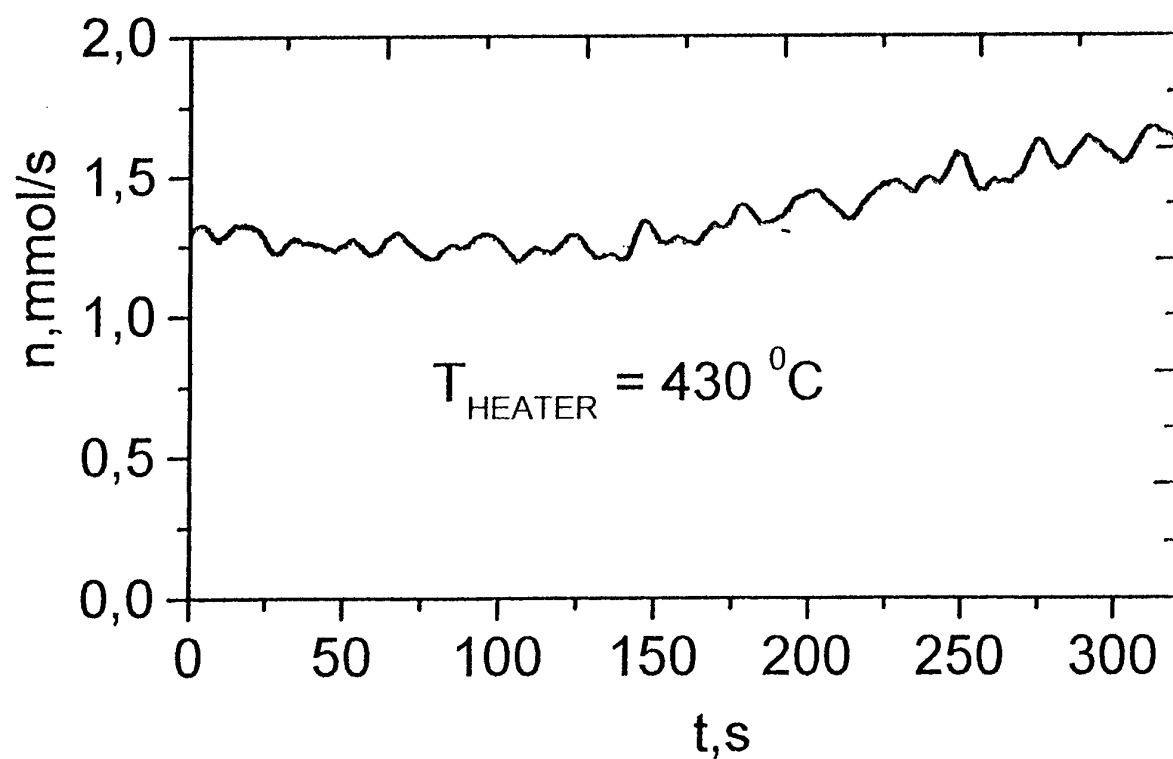
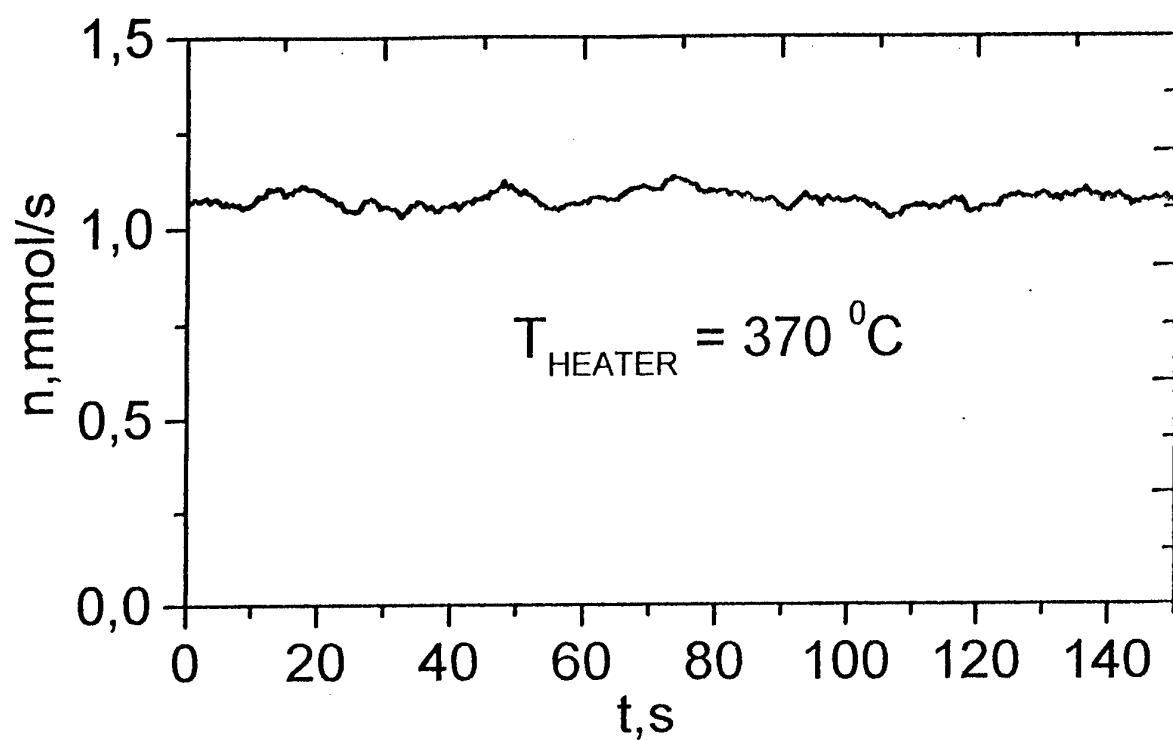


Fig.5 : Plot of  $I_2$  flowrate on time

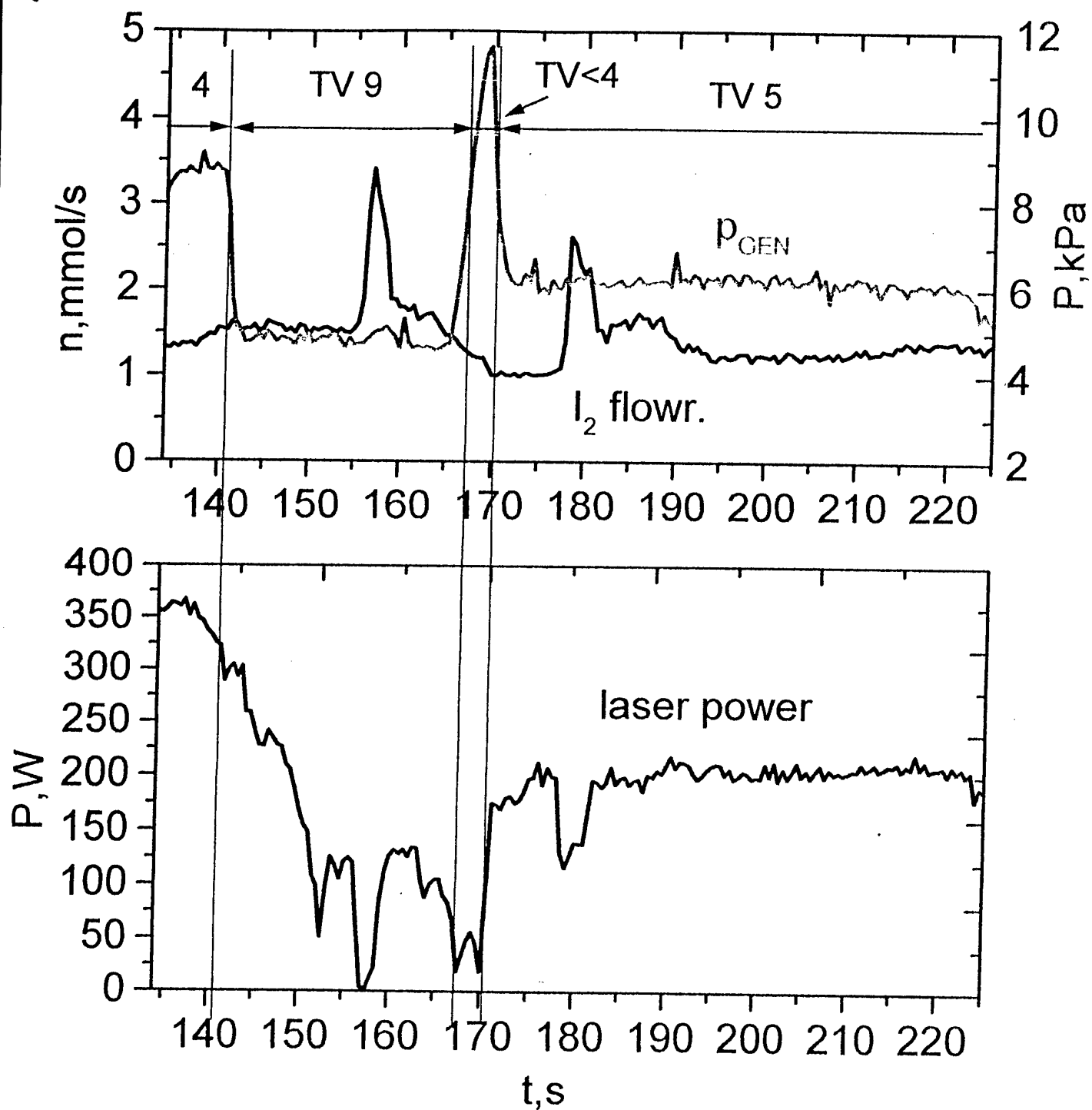


Fig.6.: Generator pressure,  $I_2$  flowrate and laser power on time

200

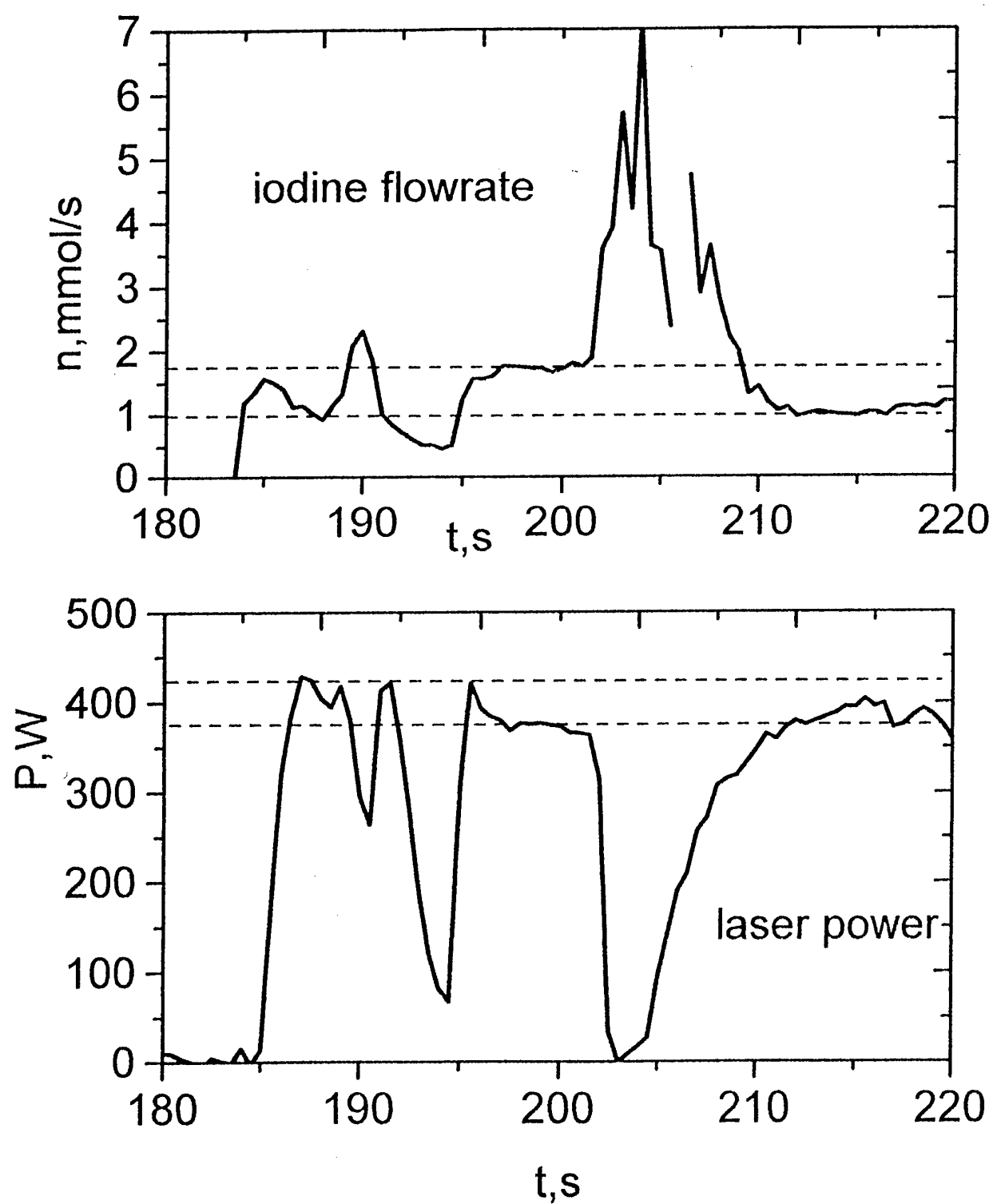


Fig.7: Iodine flowrate and laser power on time

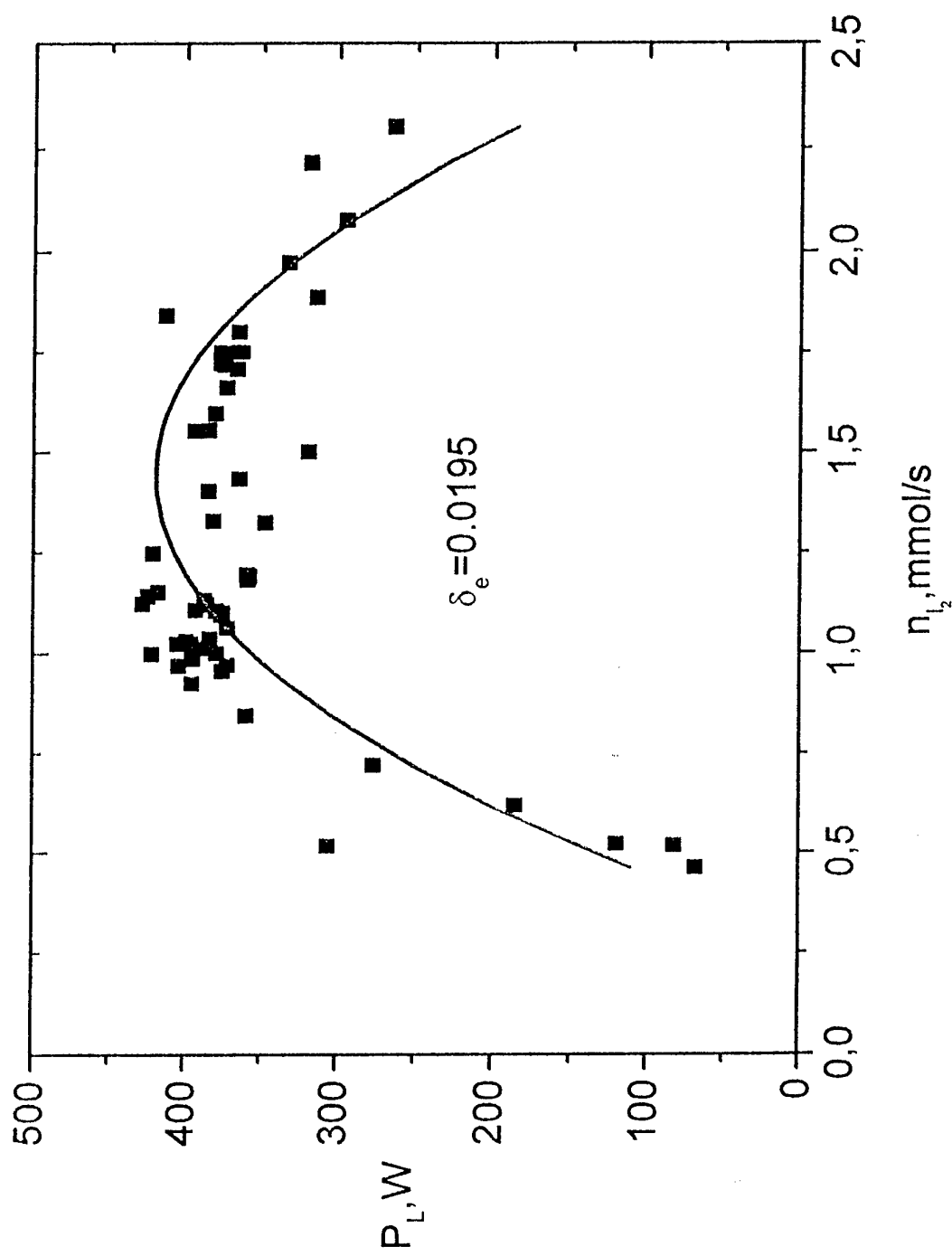


Fig.8 Laser power on iodine flowrate

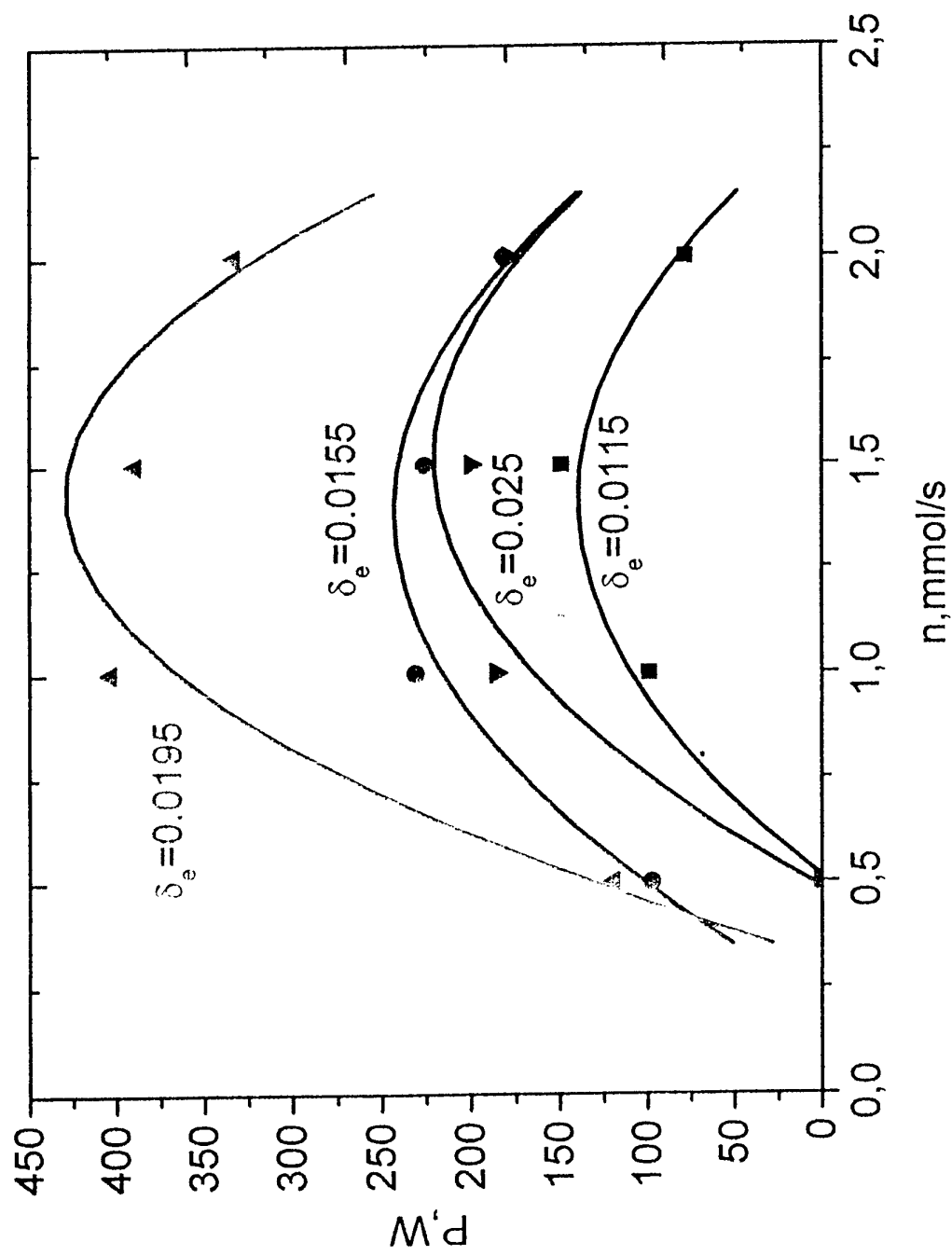


Fig.9 : Laser power on iodine flowrate for different outcoupling

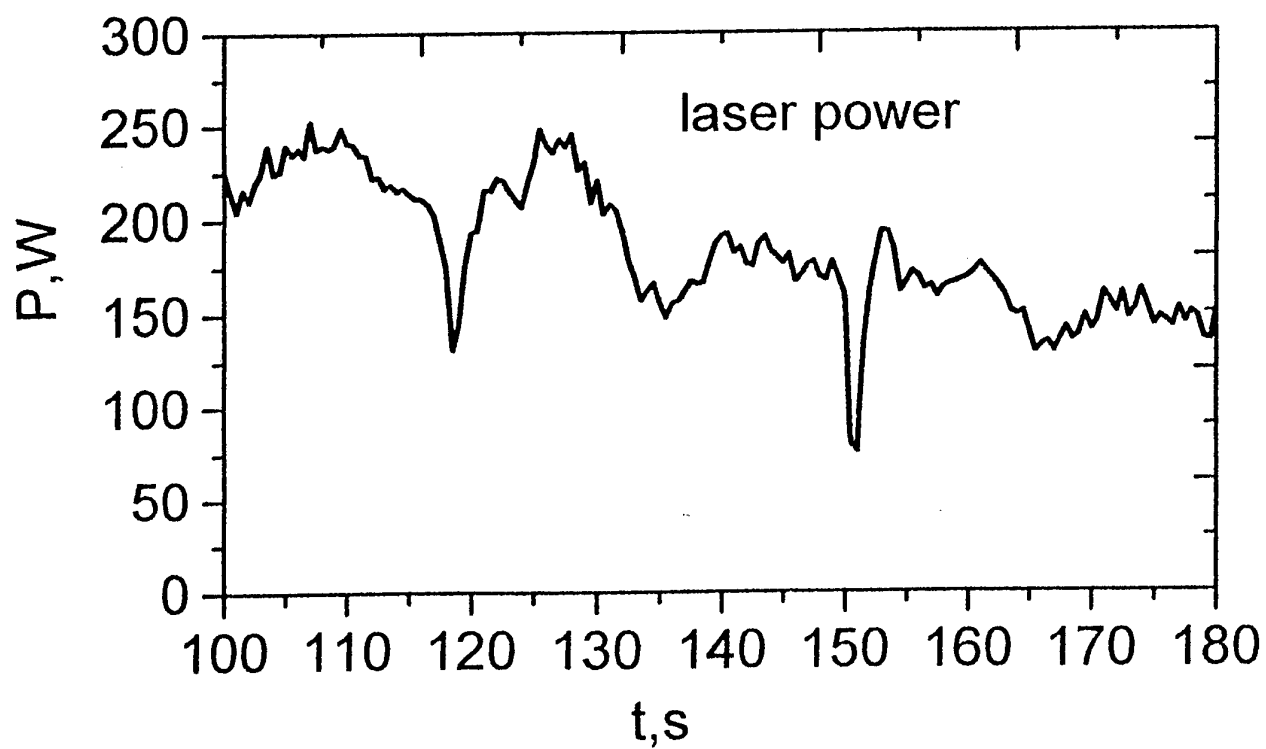
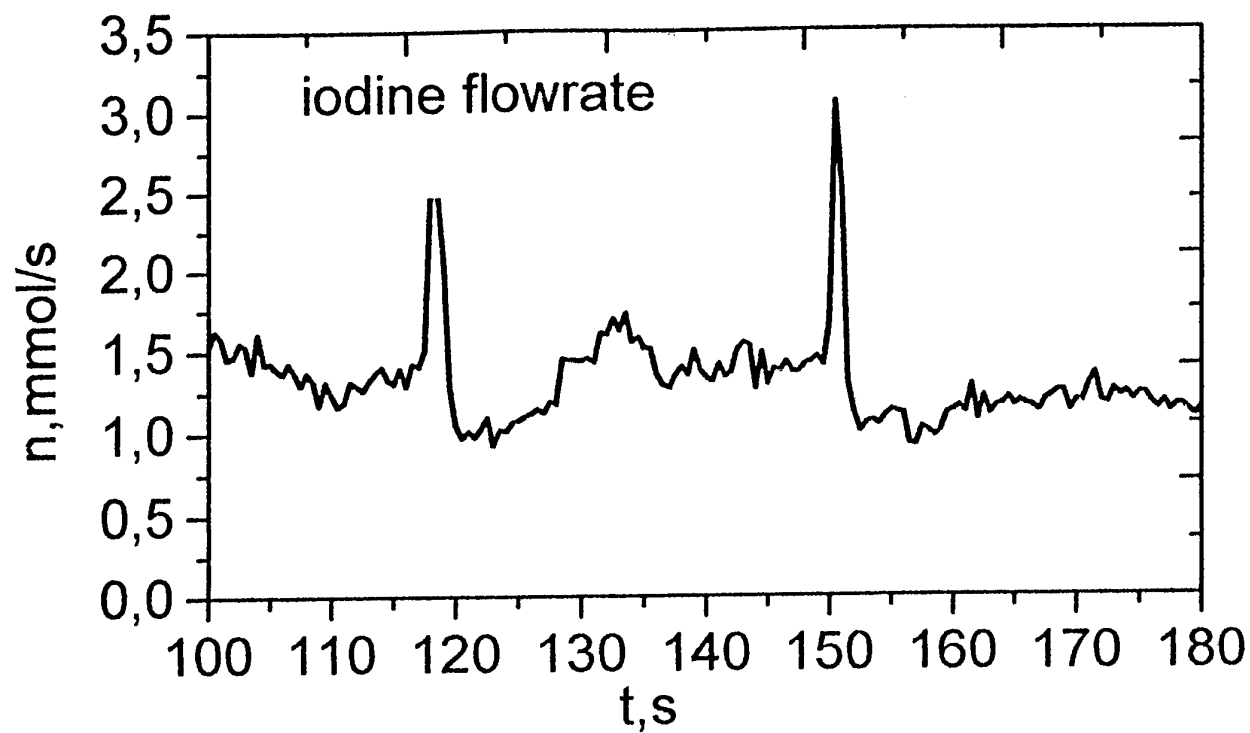


Fig.10: Iodine flowrate and laser power on time



# Results of Water Measurements at the DLR COIL

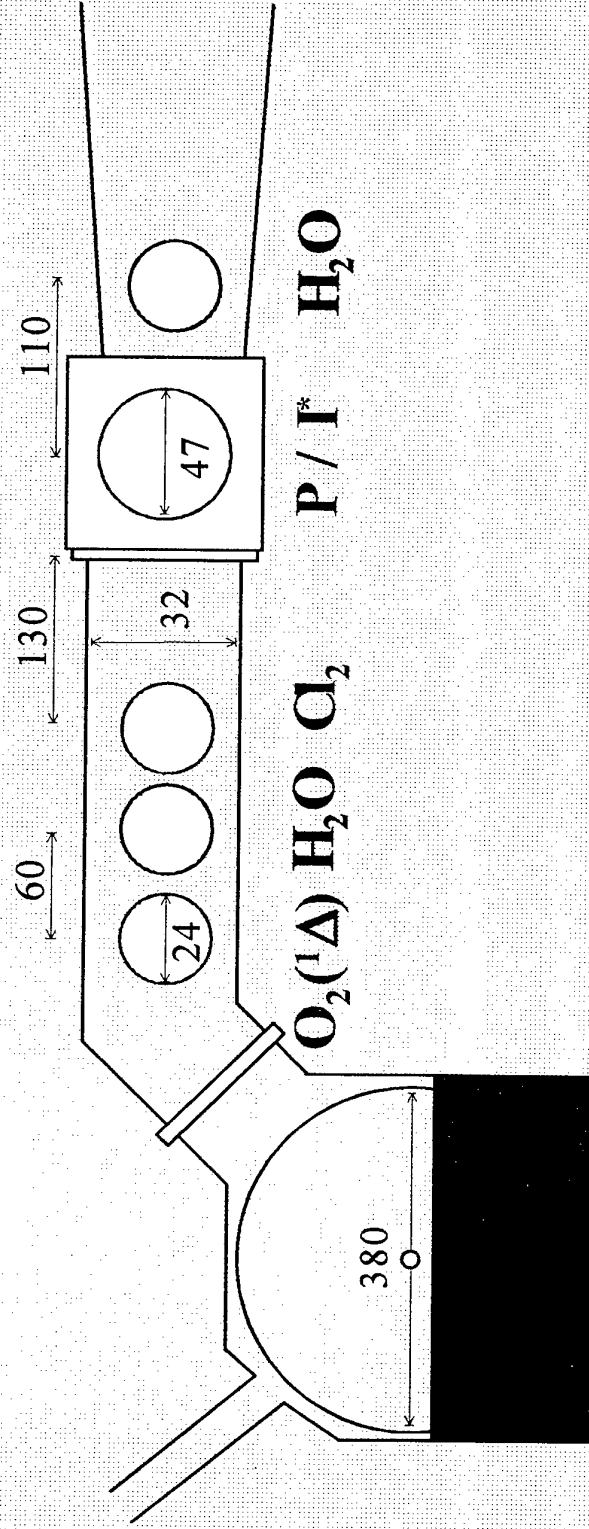
Frank Duschek, Jürgen Handke, and  
Karin Grünewald

DLR Lampoldshausen

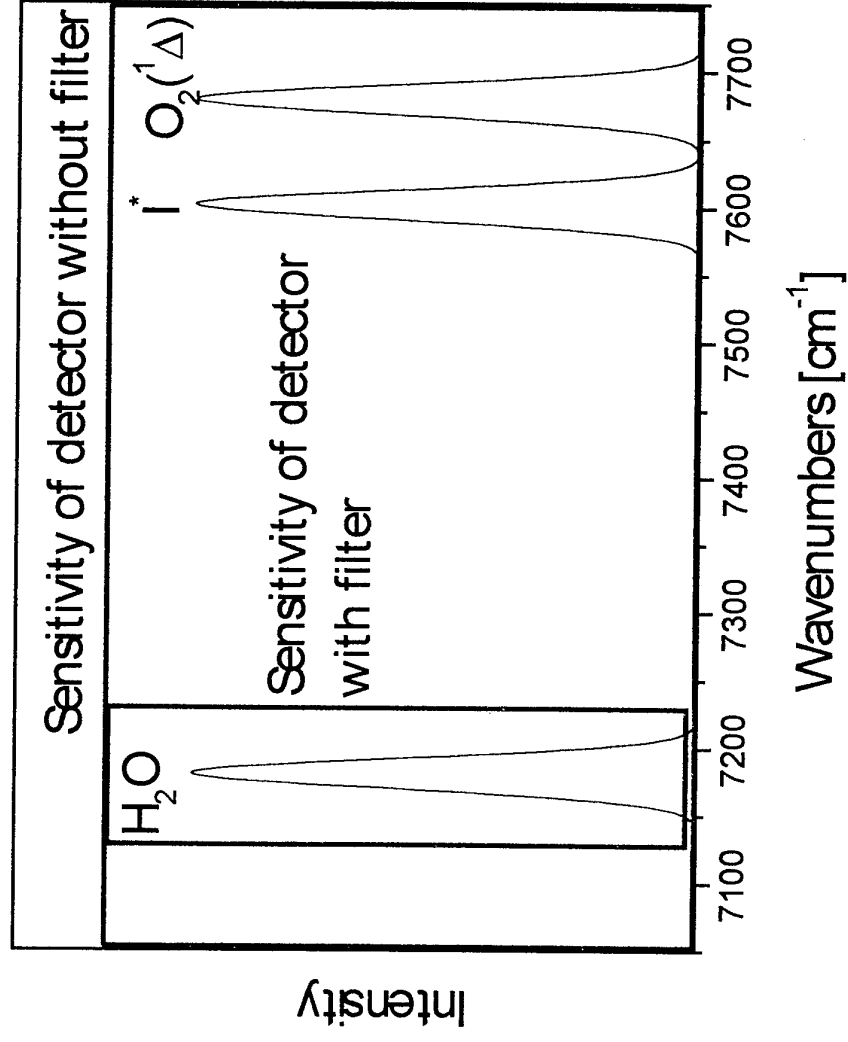
# Outline

- Experimental setup
  - Built-in filter system
  - Reproducibility
- Measurements in the duct
- Measurements in the cavity
  - Condensation of water
- Substitution of optical diagnostics by a temperature dependent water vapor model

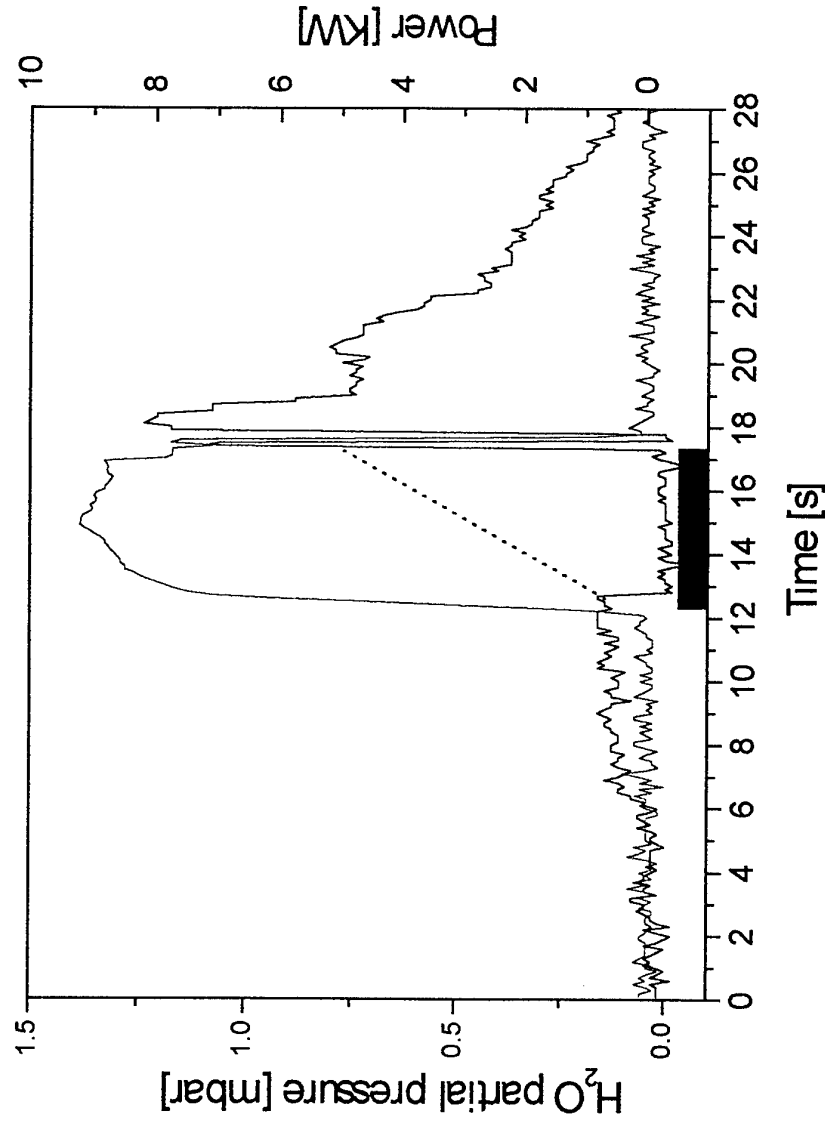
# Optical Diagnostics in the COIL



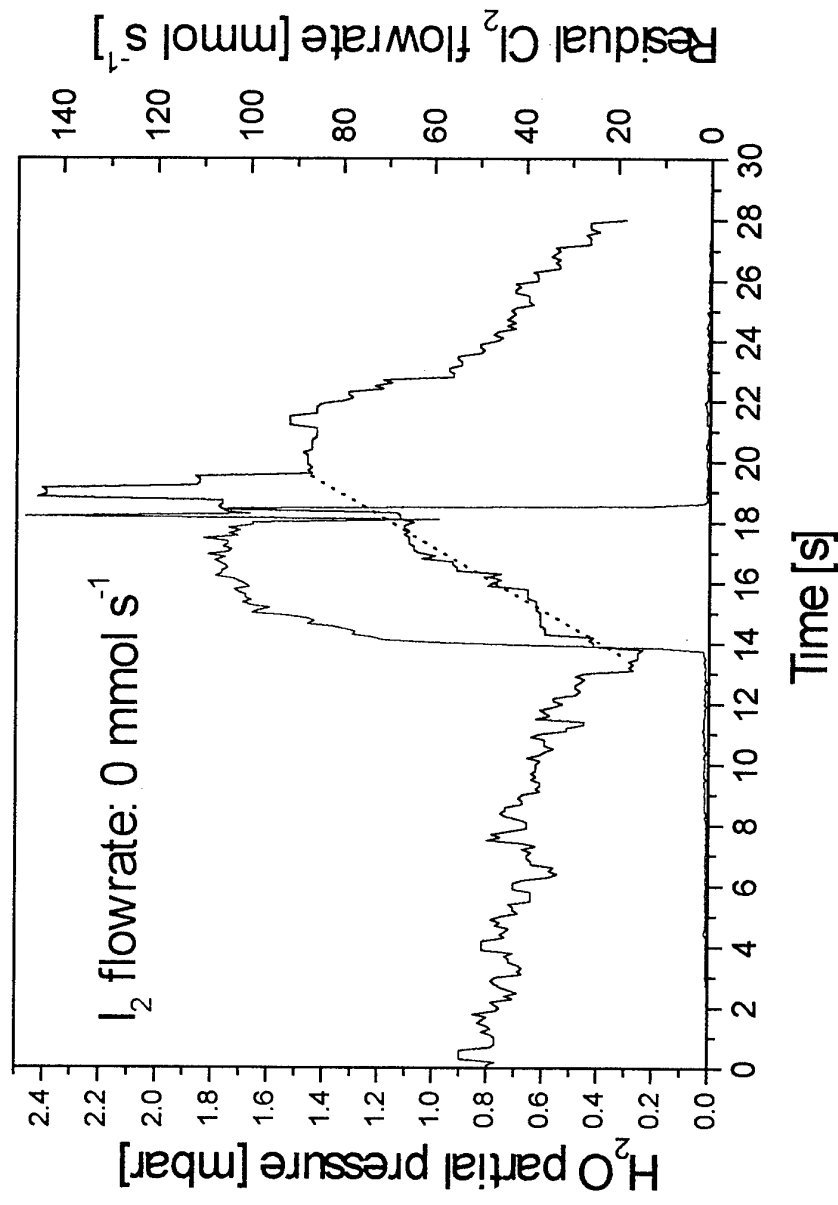
# COIL System Emission Lines near 1.3



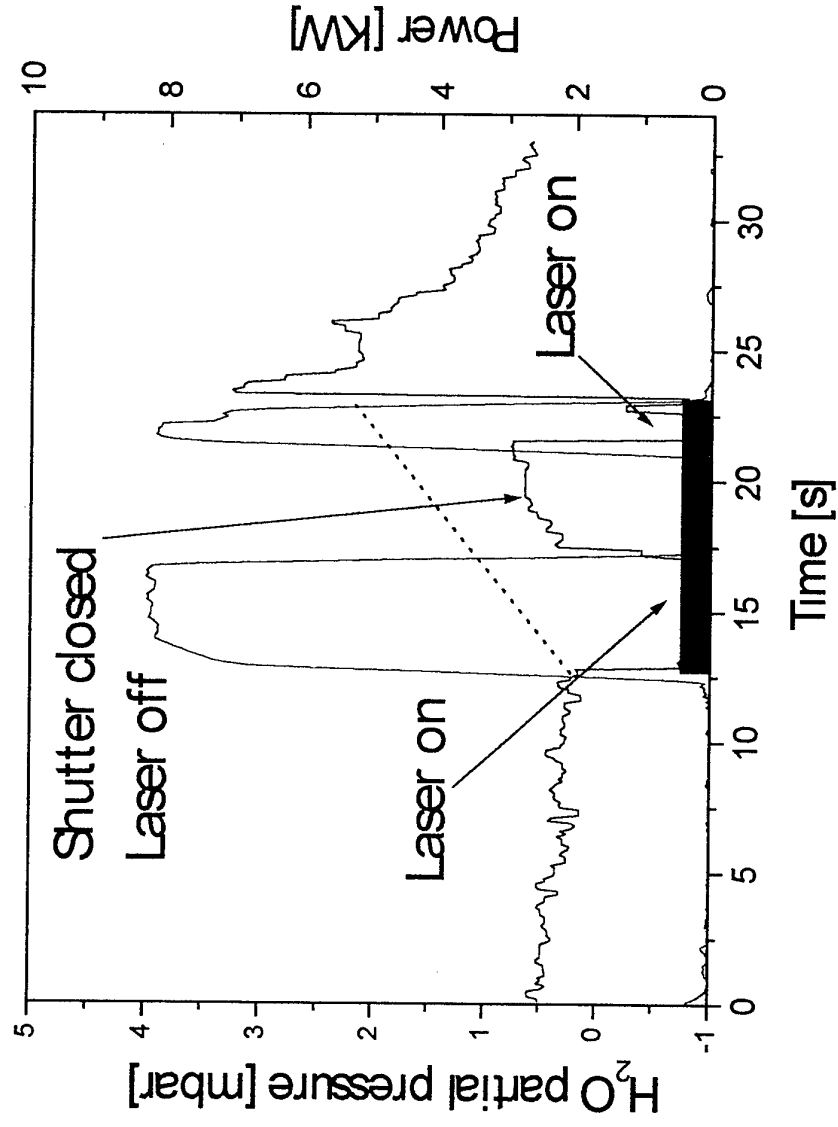
# Measurement without Bandpass Filter



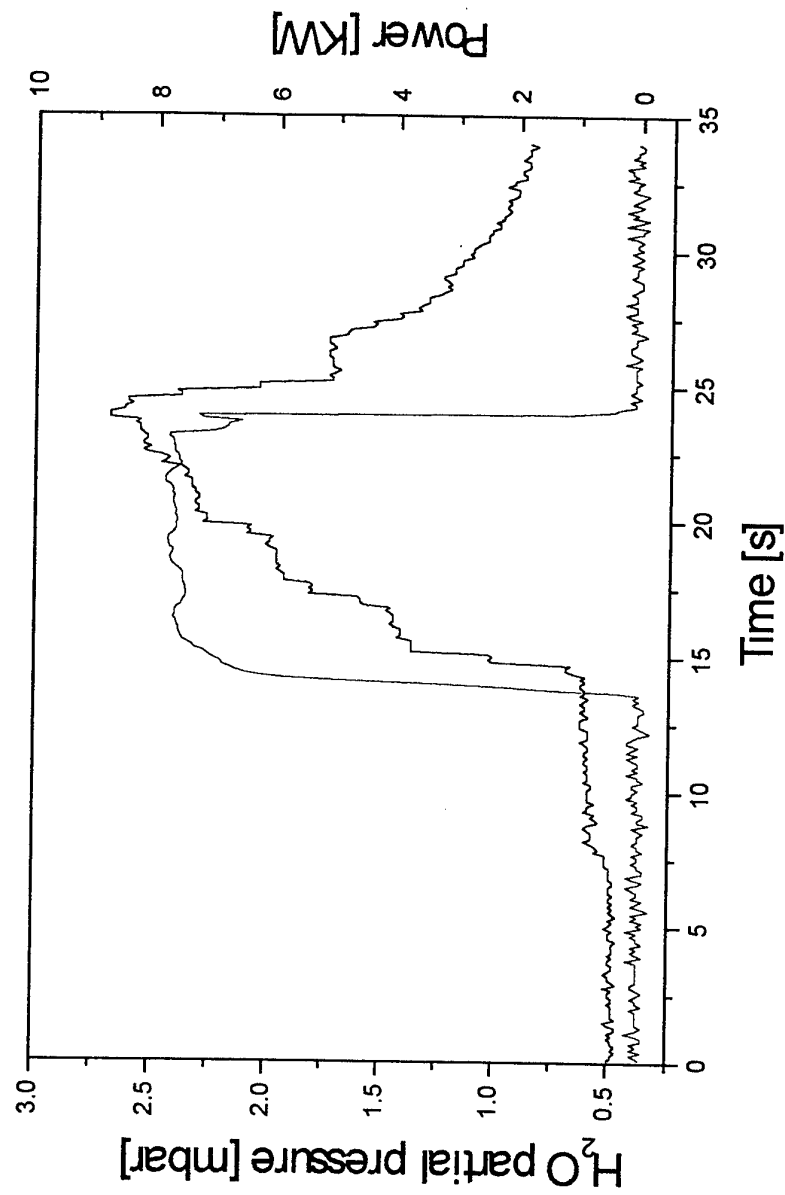
# Measurement without Bandpass Filter



# Measurement without Bandpass Filter



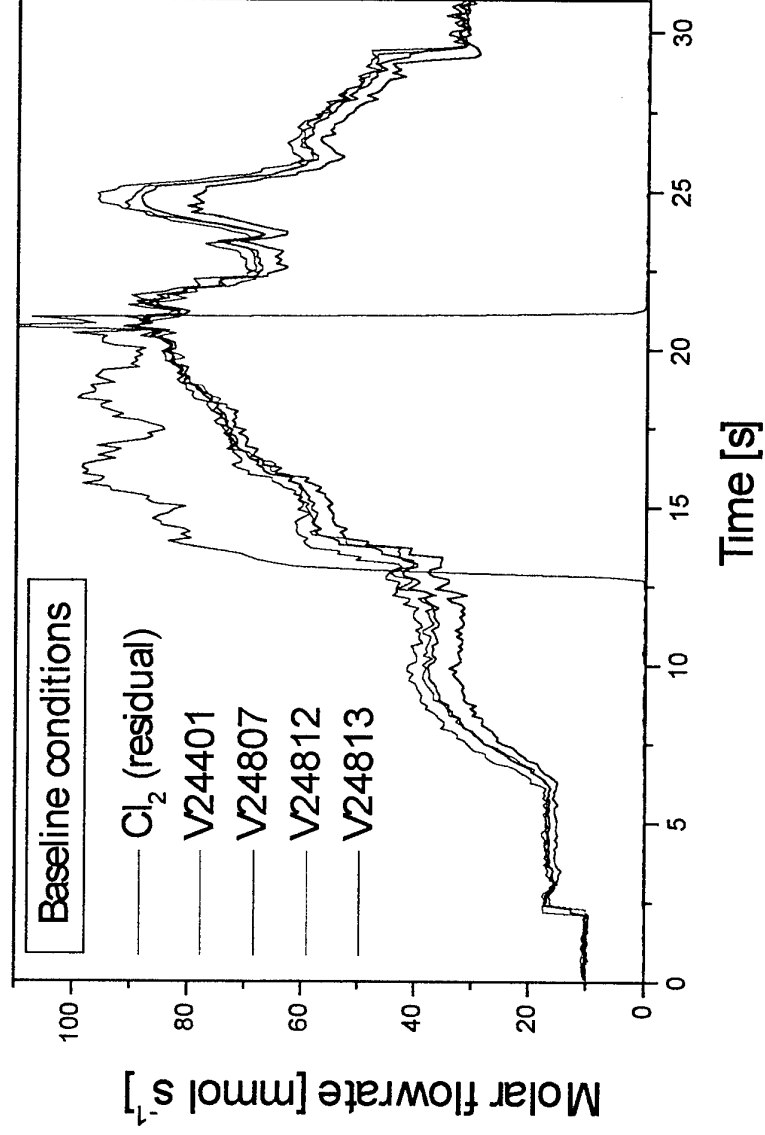
# Measurement with Bandpass Filter



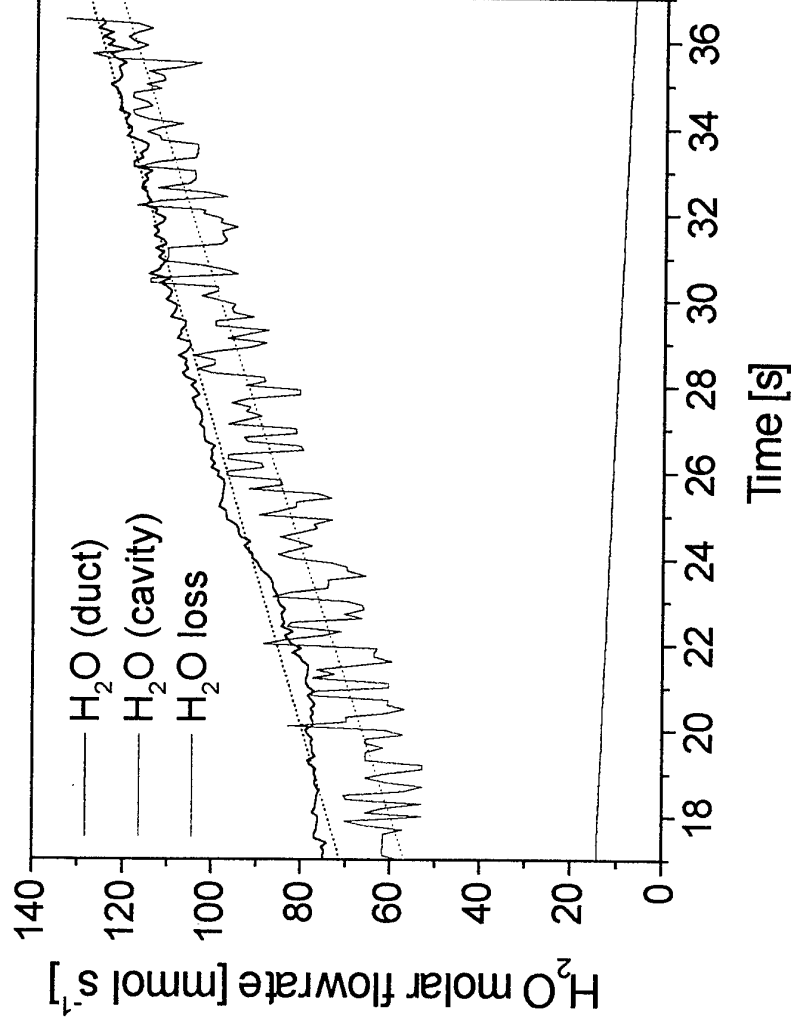


# Reproducibility

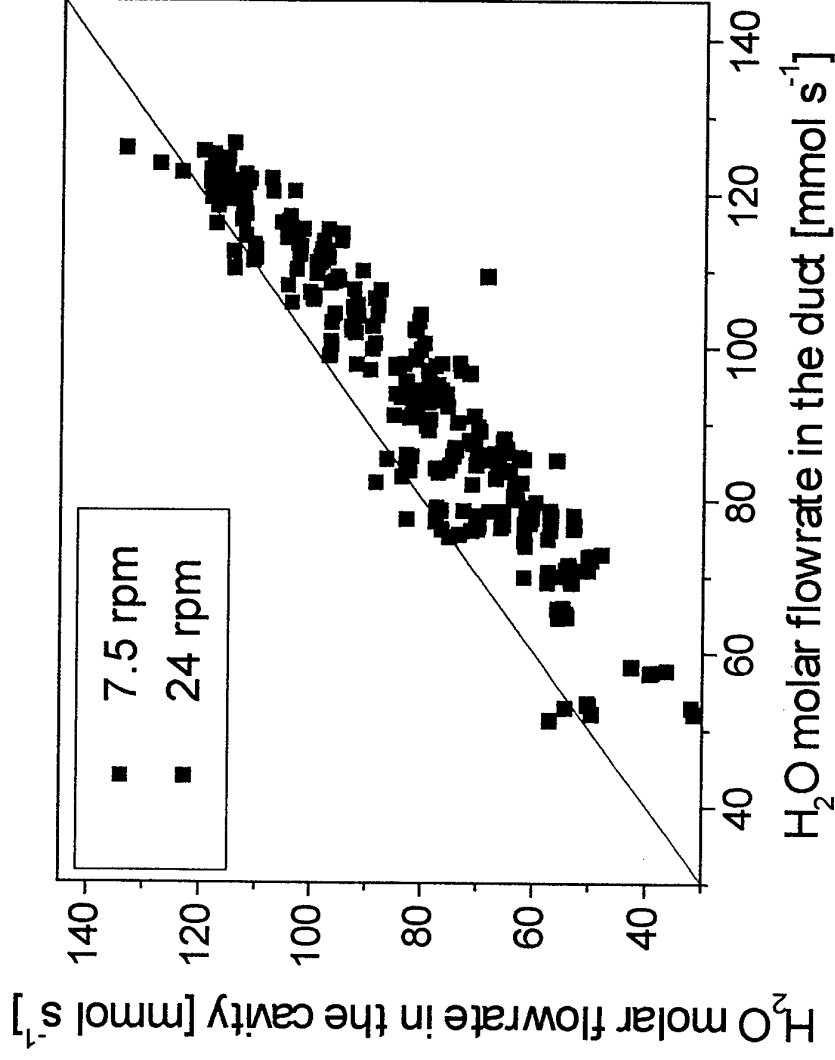
H<sub>2</sub>O molar flowrate in the duct



# Simultaneous Measurement of $\text{H}_2\text{O}$ in Duct and Cavity



# Correlation between $\text{H}_2\text{O}$ in Duct and Cavity including different Disk Package Rotation Rates



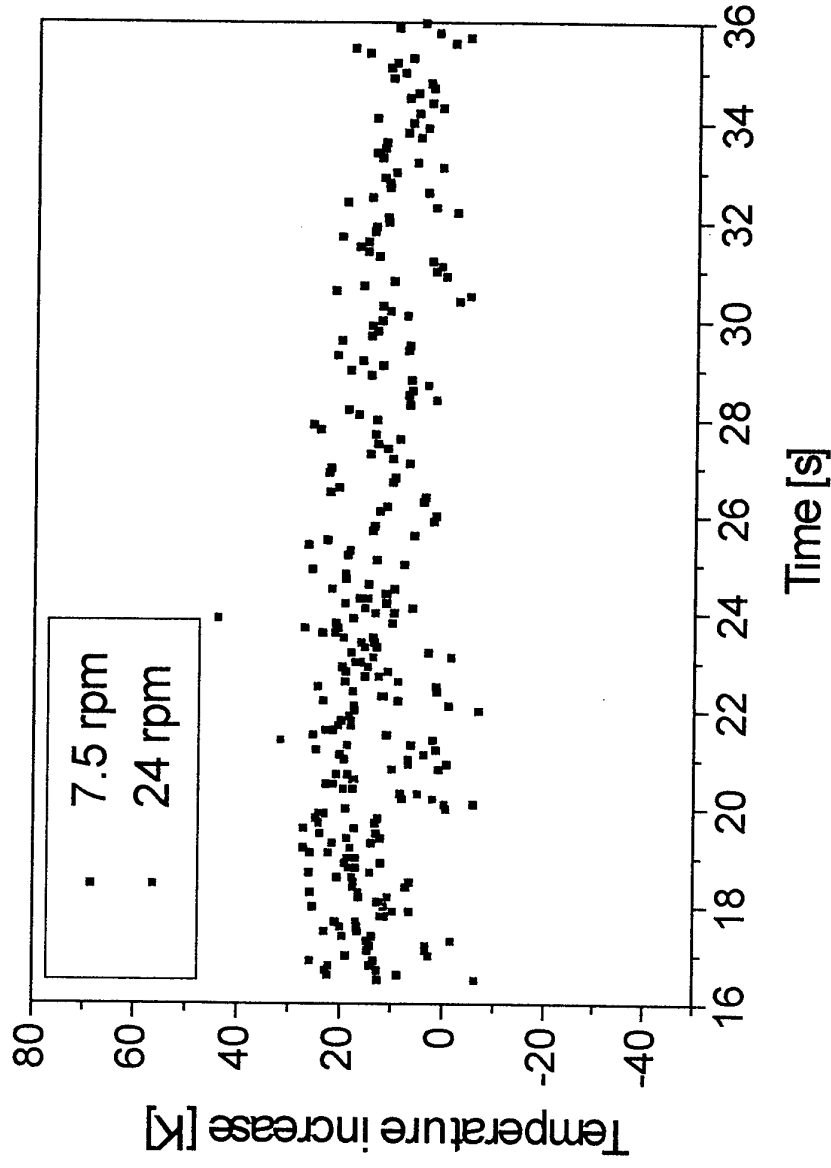
# Temperature Change in the Cavity

- Thermodynamical calculation

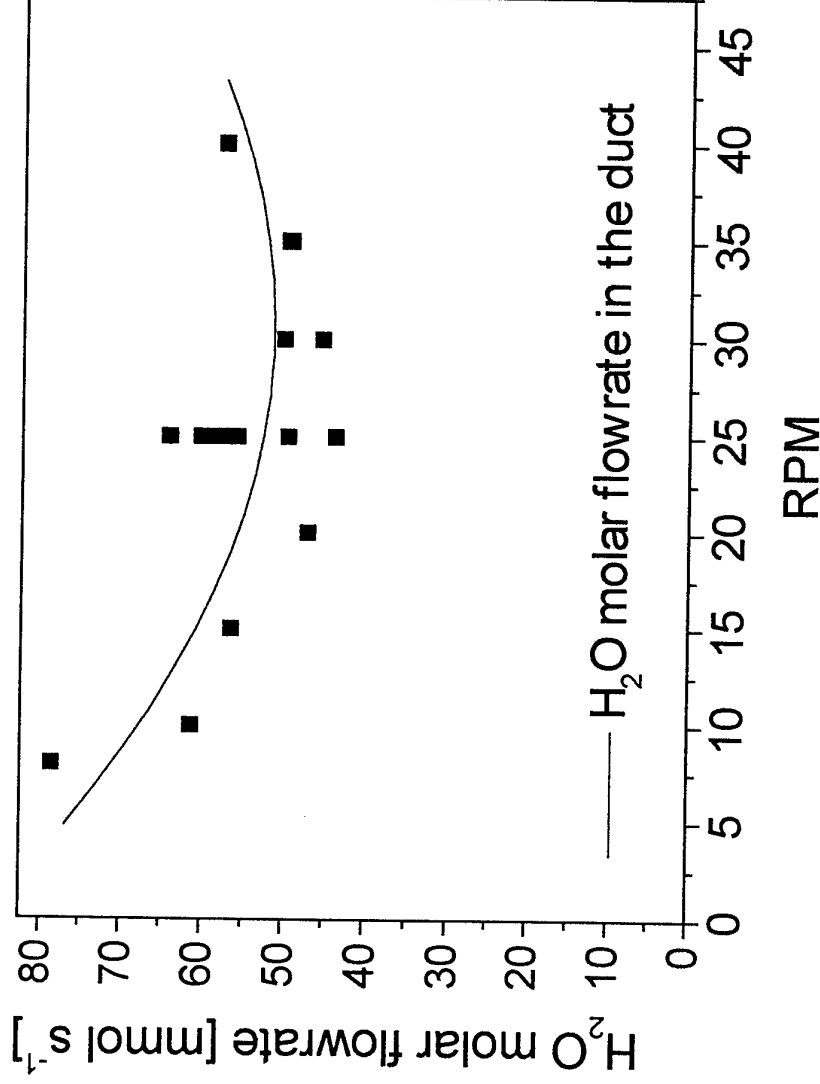
$$\begin{aligned}\Delta H_{g \rightarrow l} + \Delta H_{l \rightarrow s} &= C_p \Delta T \\ &= \sum_i n_i c_{p,i} \Delta T\end{aligned}$$

- $i = \text{He, O}_2, \text{Cl}_2, \text{I}_2, \text{H}_2\text{O}, \dots$

# Temperature Change in the Cavity

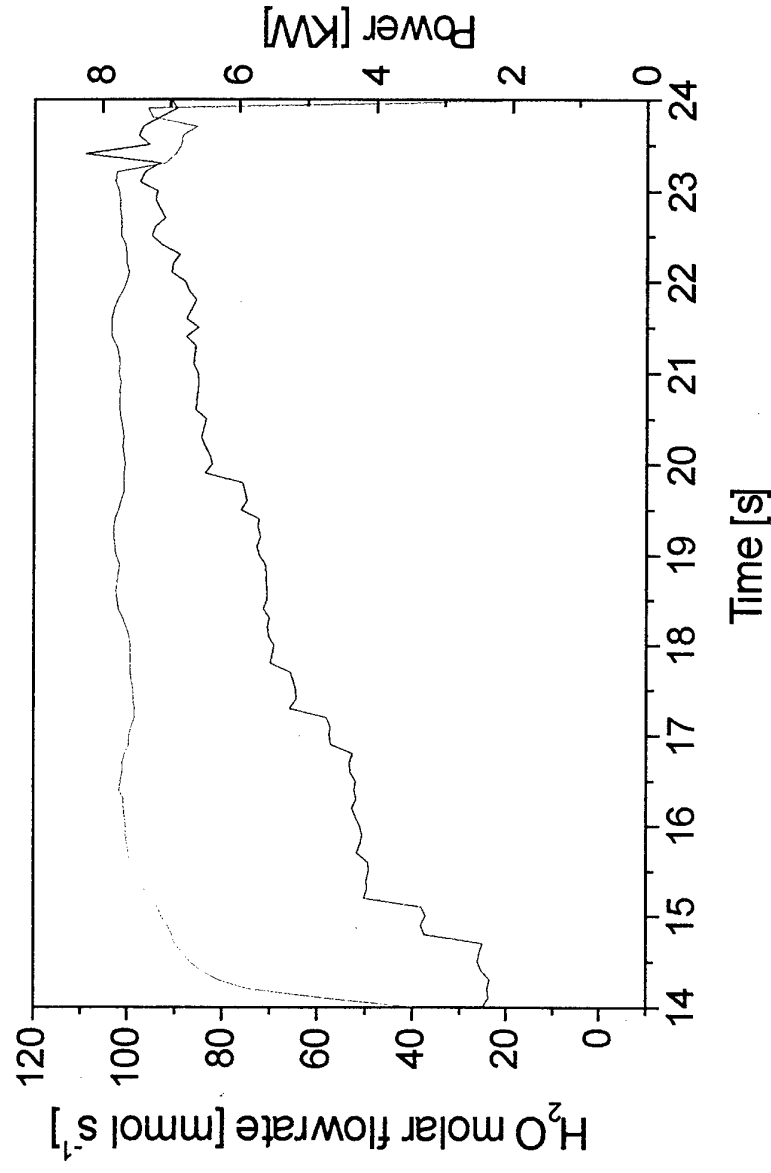


# Influence of Disk Rotation Speed on the Water Content in the Duct



# Influence of $\text{H}_2\text{O}$ on the Output Power

## Short Time Operation



# Empirical Function for Modeling H<sub>2</sub>O Vapor Pressure\*

$$p_{H_2O} = 10^{aT^{-1} + b + cT + dT^2}$$

$$a = 9.758496 \text{ K}$$

$$b = -2755.526$$

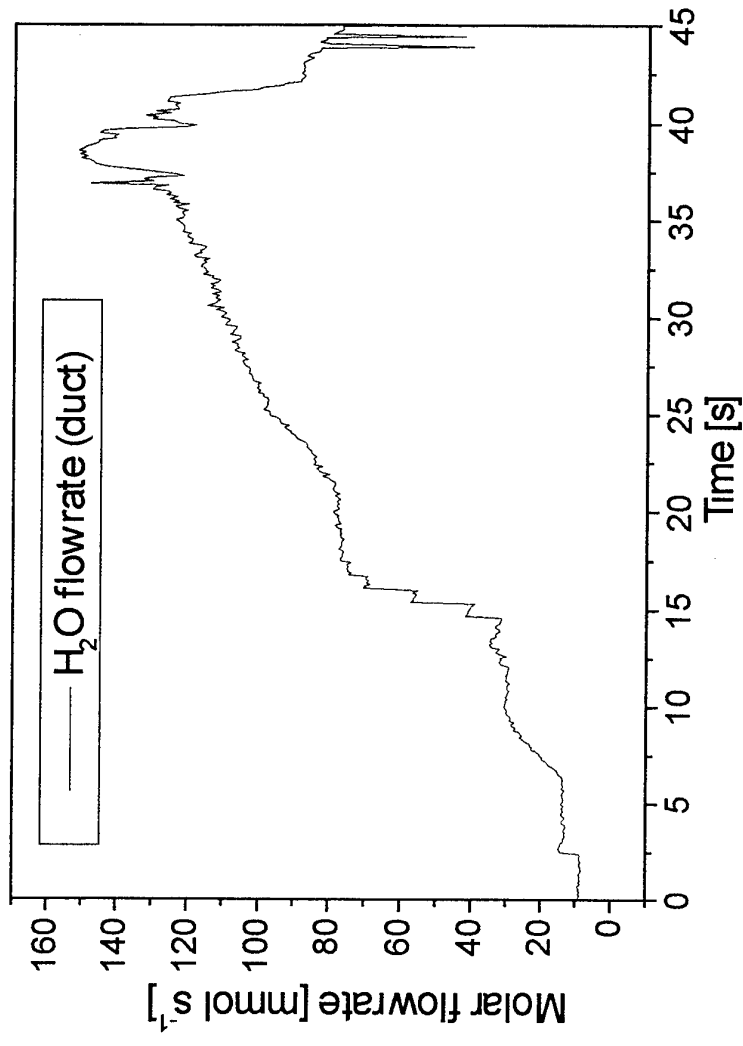
$$c = -8.410066 \times 10^{-3} \text{ K}^{-1}$$

$$d = 5.529658 \times 10^{-6} \text{ K}^{-2}$$

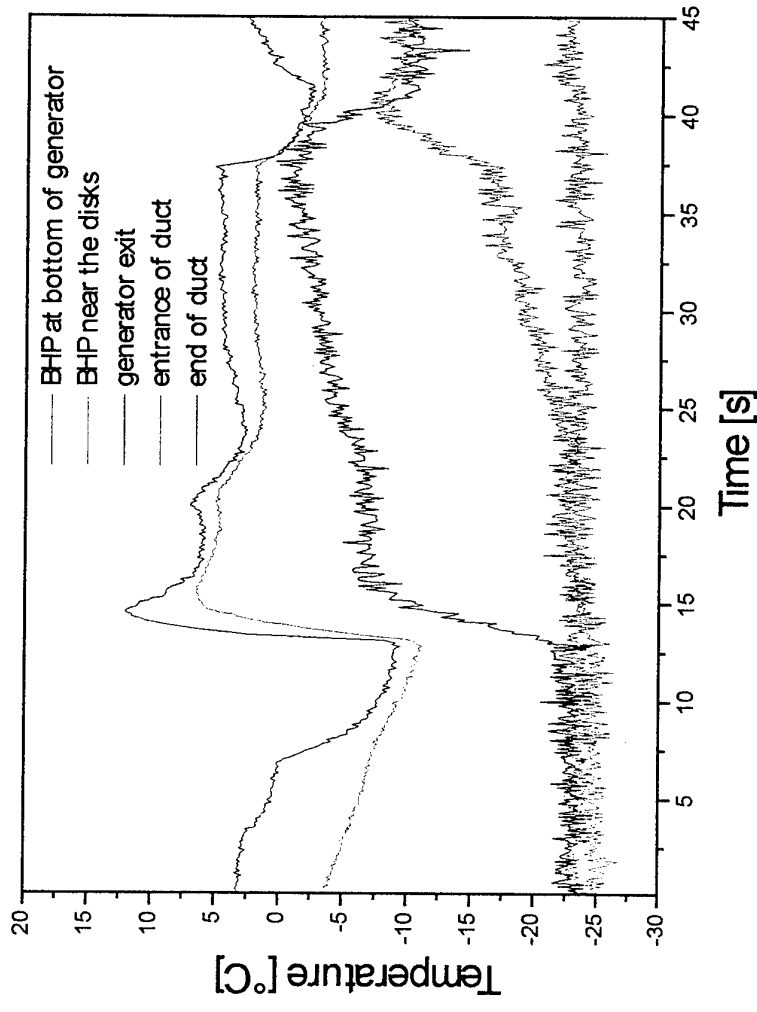
\* Ref.: Gase Handbuch, Messer-Griesheim GmbH, Frankfurt,  
1989



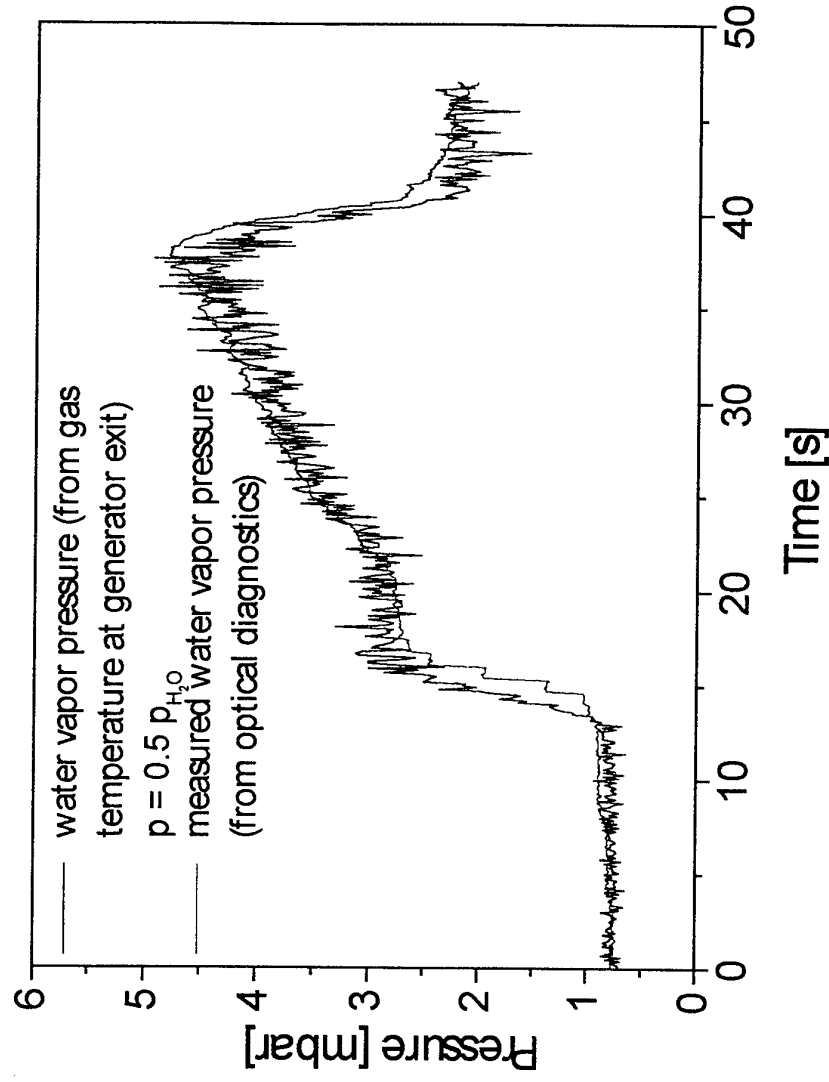
# Modeling $\text{H}_2\text{O}$ Pressure



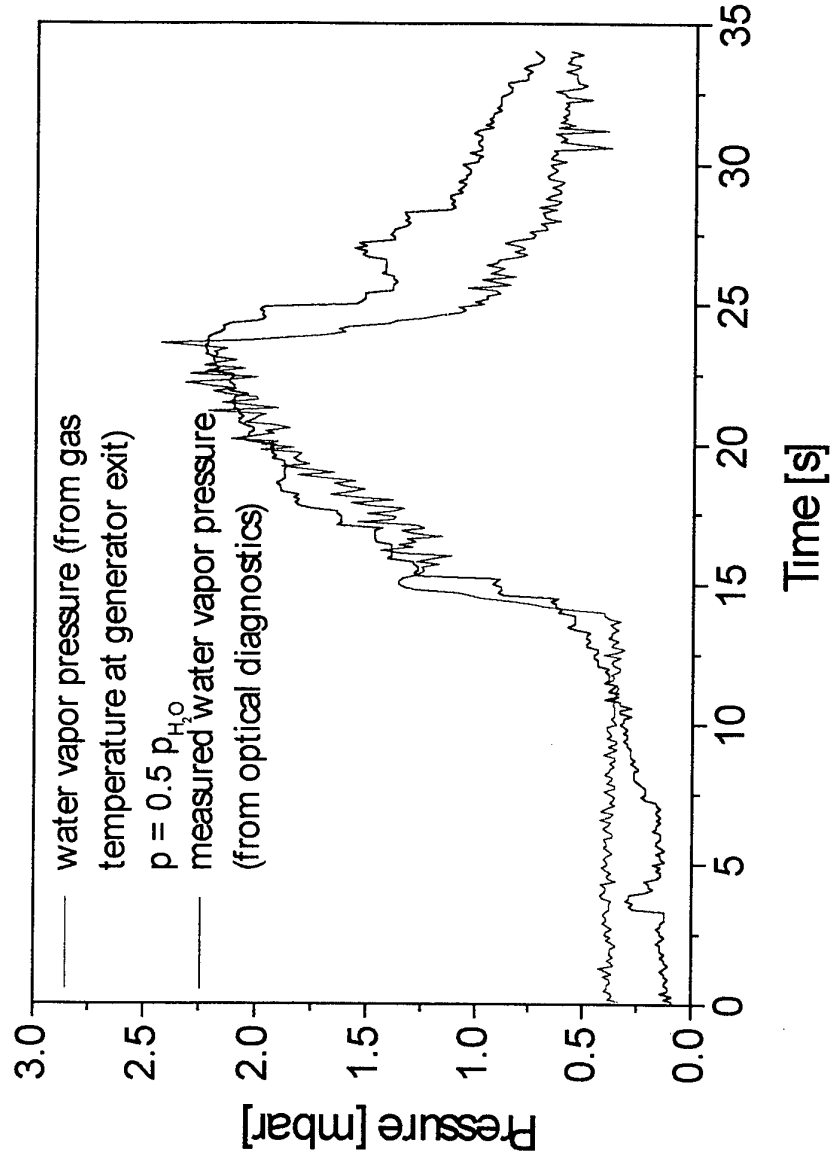
# Temperatures for Modeling H<sub>2</sub>O Pressure



# Modeling $\text{H}_2\text{O}$ Pressure from Measured Temperatures



# Modeling $\text{H}_2\text{O}$ Pressure from Measured Temperatures



## Results

- ▶ H<sub>2</sub>O measurement without a filter system may lead to wrong water vapor pressures. This can be avoided with optical filter systems.
- ▶ Maximum 10-20 % of water condenses in the cavity.
- ▶ Increasing He and Cl<sub>2</sub> flow leads to higher water content.
- ▶ Disk rotation speed has minimum water in the laser gas at 24-30 rpm.
- ▶ Gas temperature at generator exit can be used to describe the water pressure.

# **GAIN DIAGNOSTIC IN A SUPERSONIC COIL WITH TRANSONIC INJECTION OF IODINE**

D. Furman, E. Bruins, B. D. Barmashenko and S. Rosenwaks

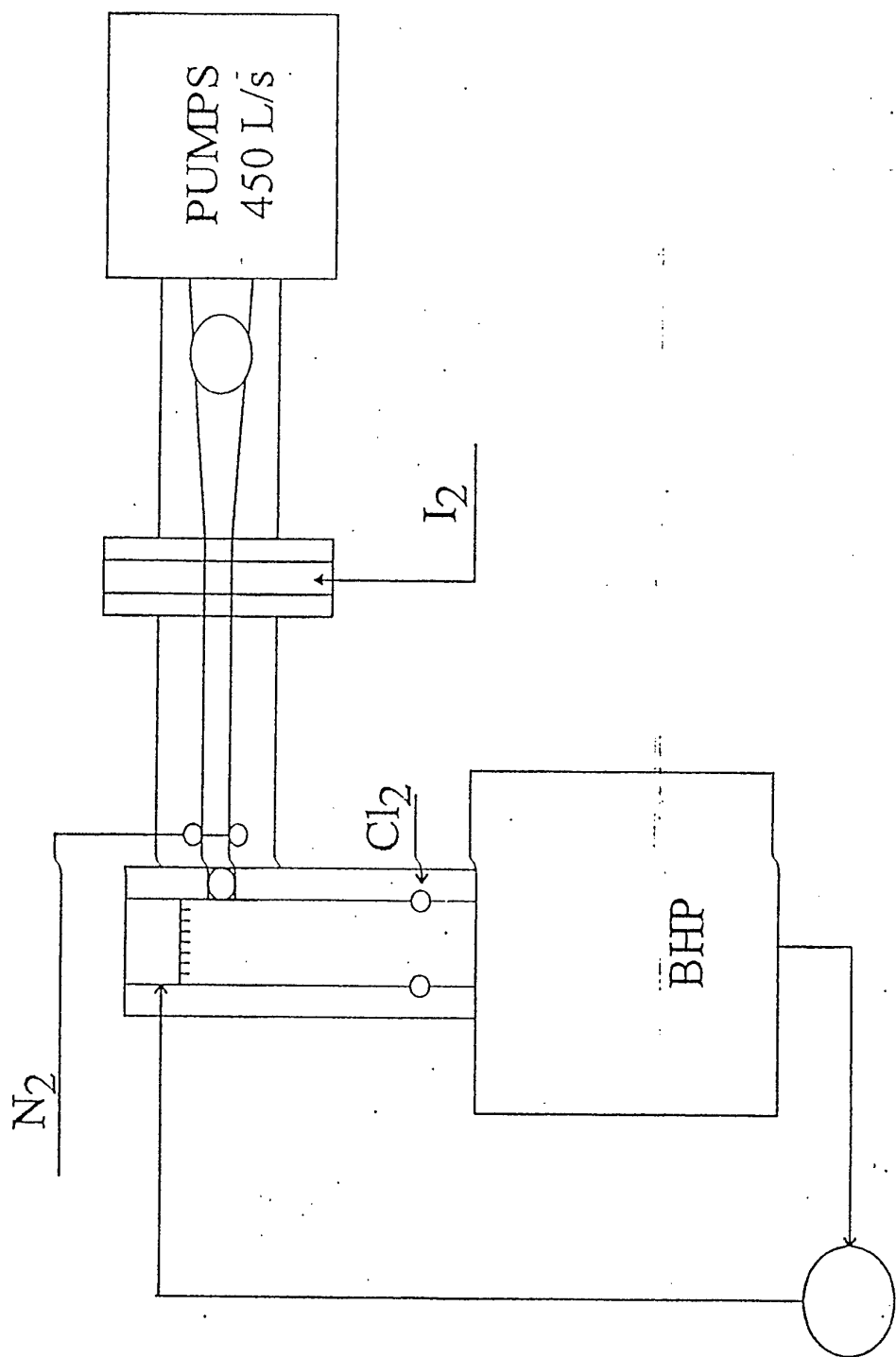
Department of Physics,  
Ben-Gurion University of the Negev,  
Beer-Sheva, Israel

A 5-cm gain length supersonic COIL with maximum chlorine flow rate of 20 mmole/s.

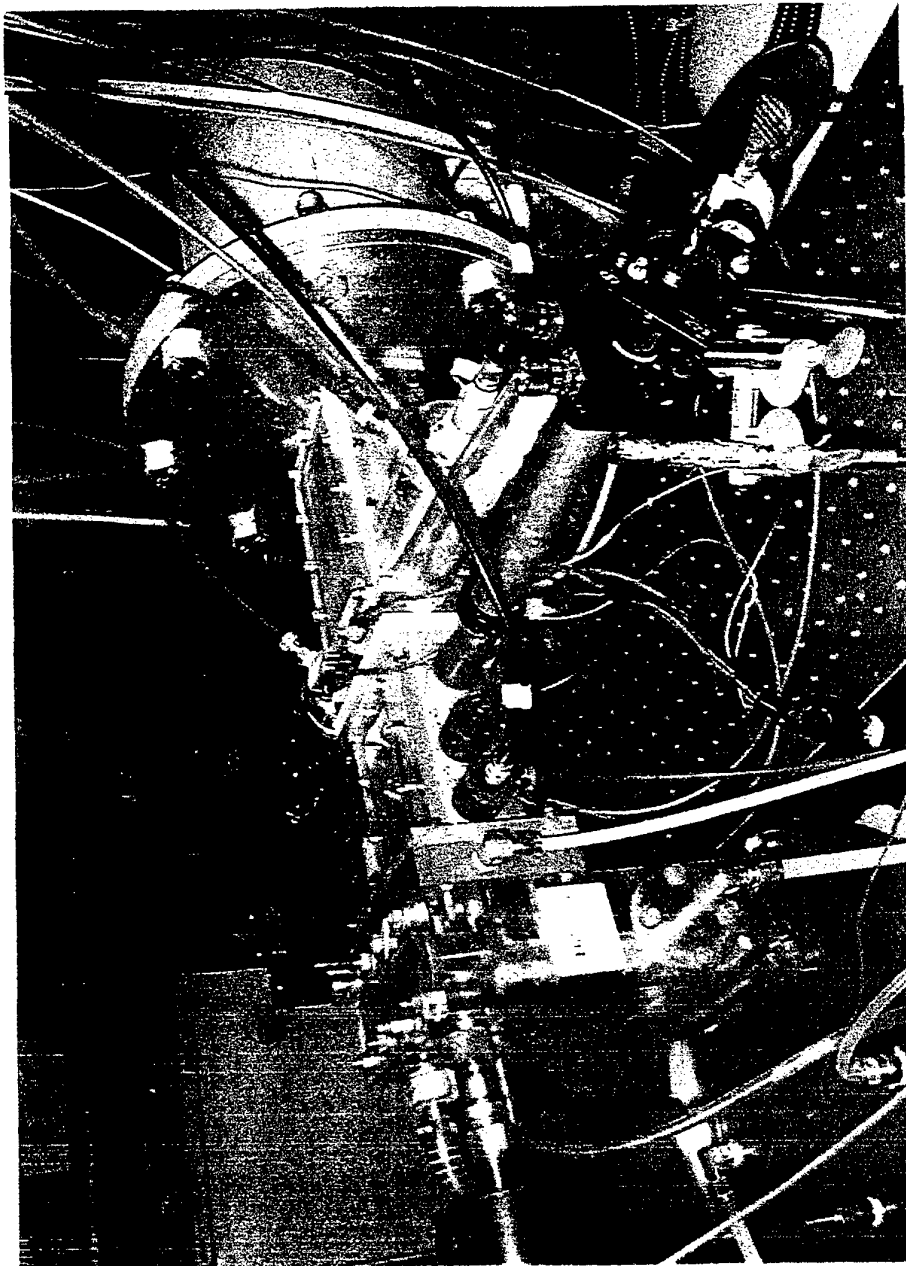
Energized by a jet type singlet oxygen generator (JSOG).

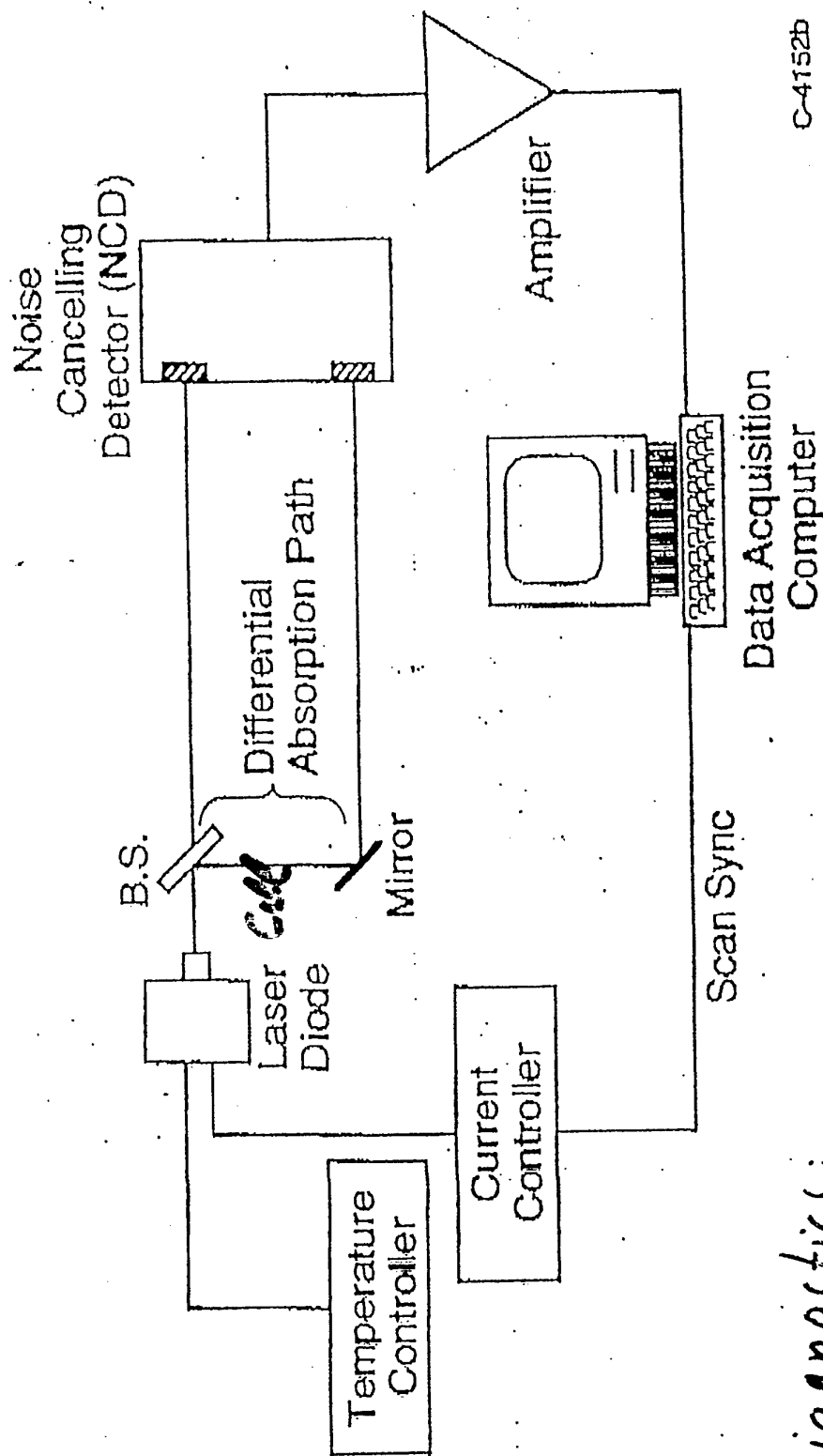
Efficiently operates without a buffer gas (using transonic mixing of iodine)

Output power of 210 W with chemical efficiency of 20% was obtained with chlorine flow rate of 11.8 mmole/s.







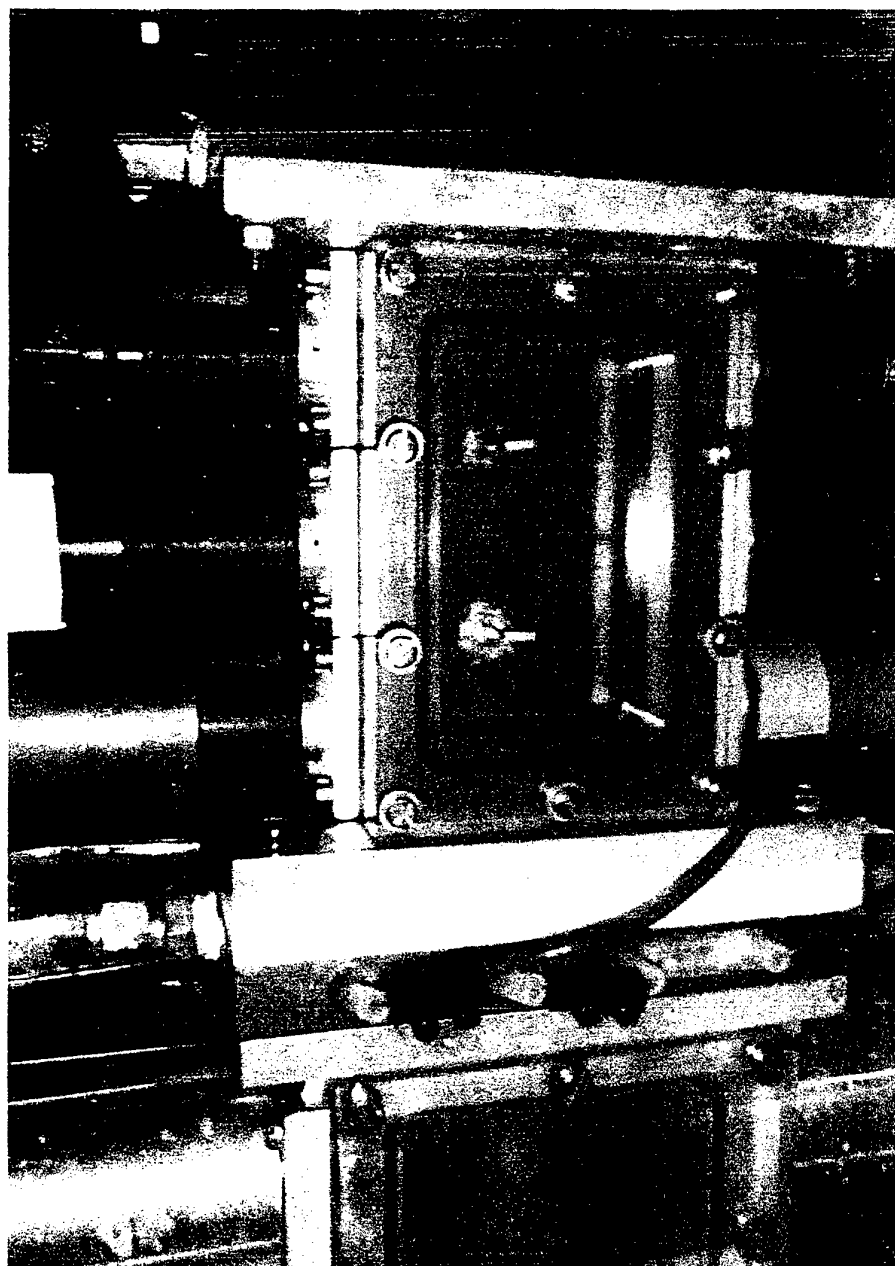


Diagnostics:

$O_2(^3\Sigma \rightarrow ^1\Sigma), 760 \text{ nm}$

$I(^2P_{3/2} \rightarrow ^2P_{1/2}), 1315 \text{ nm}$

$H_2O(\nu_1 + \nu_3), 1390 \text{ nm}$



## Injection Nozzles

i) Grid nozzle (transonic injection) consists of 10 rectangular brass tubes. There are 9 iodine injection holes, 0.5 mm i. d., on both sides of each tube (5 on one side and 4 on the other).

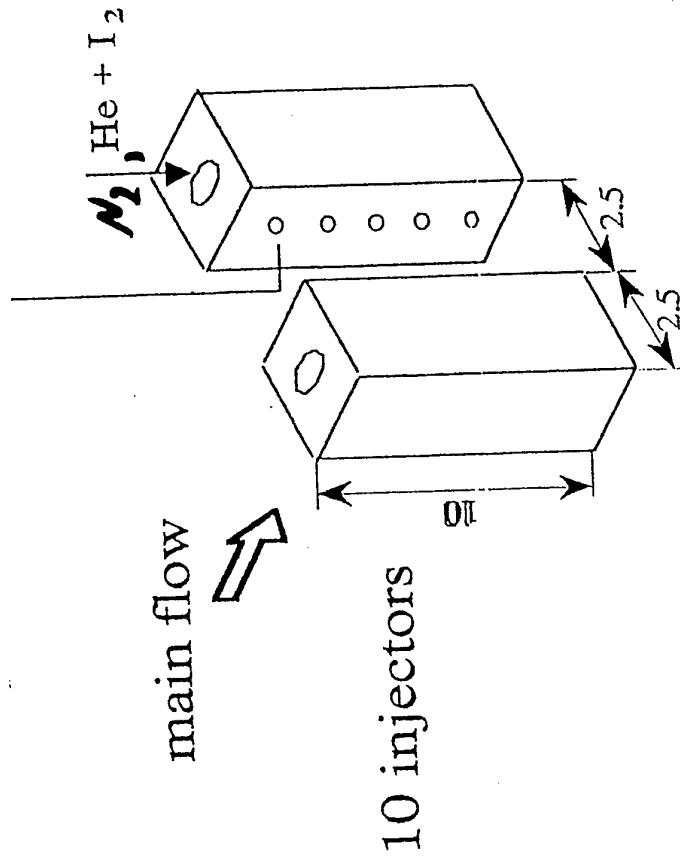
Slit Nozzle No.1 (transonic injection): the first row has 24, 0.6 mm diameter holes, and the second row has 25, 0.4 mm diameter holes.

Slit Nozzle No.2 (transonic injection): the first row has 31, 0.6 mm diameter holes, and the second row 62, 0.4 mm diameter holes.

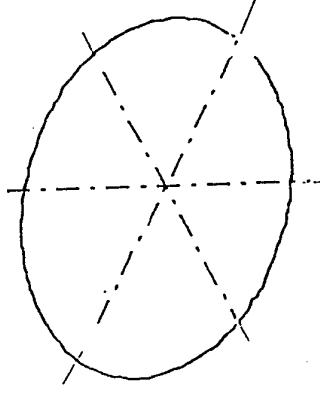
Slit Nozzle No.3 (supersonic injection): the first row has 49, 0.5 mm diameter holes, and the second row 50, 0.5 mm diameter holes.

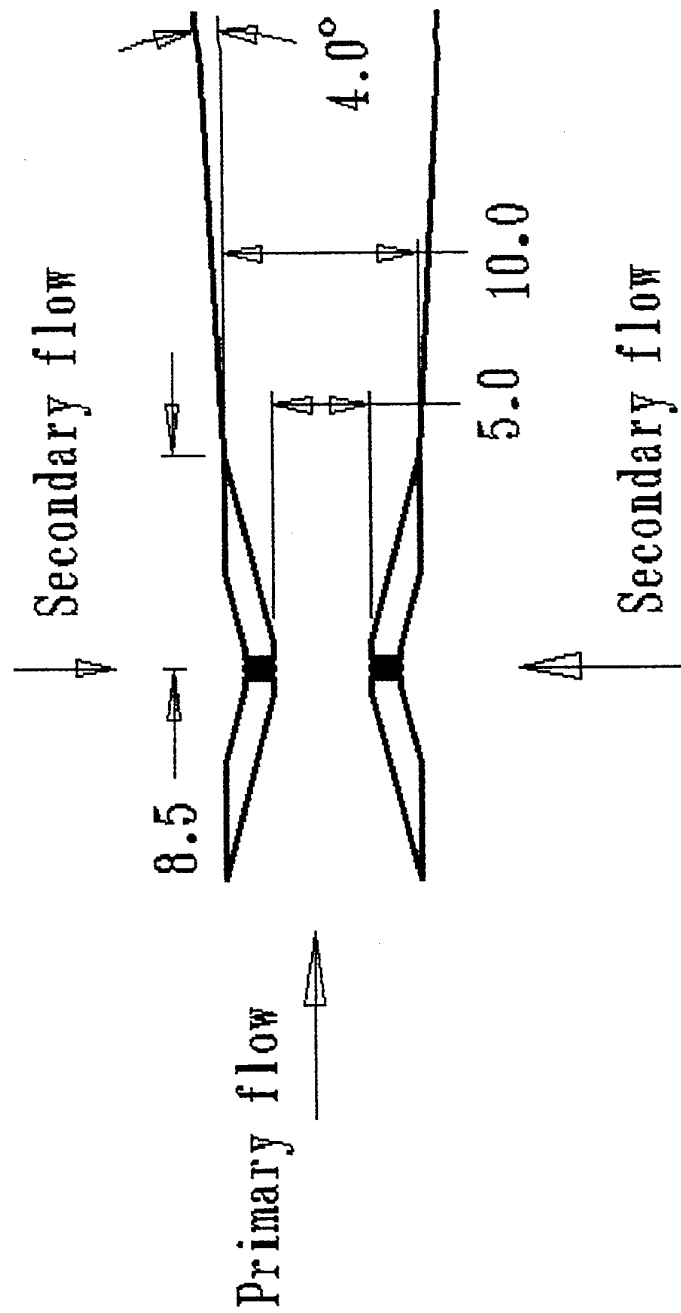
# Rectangular Brass Nozzles

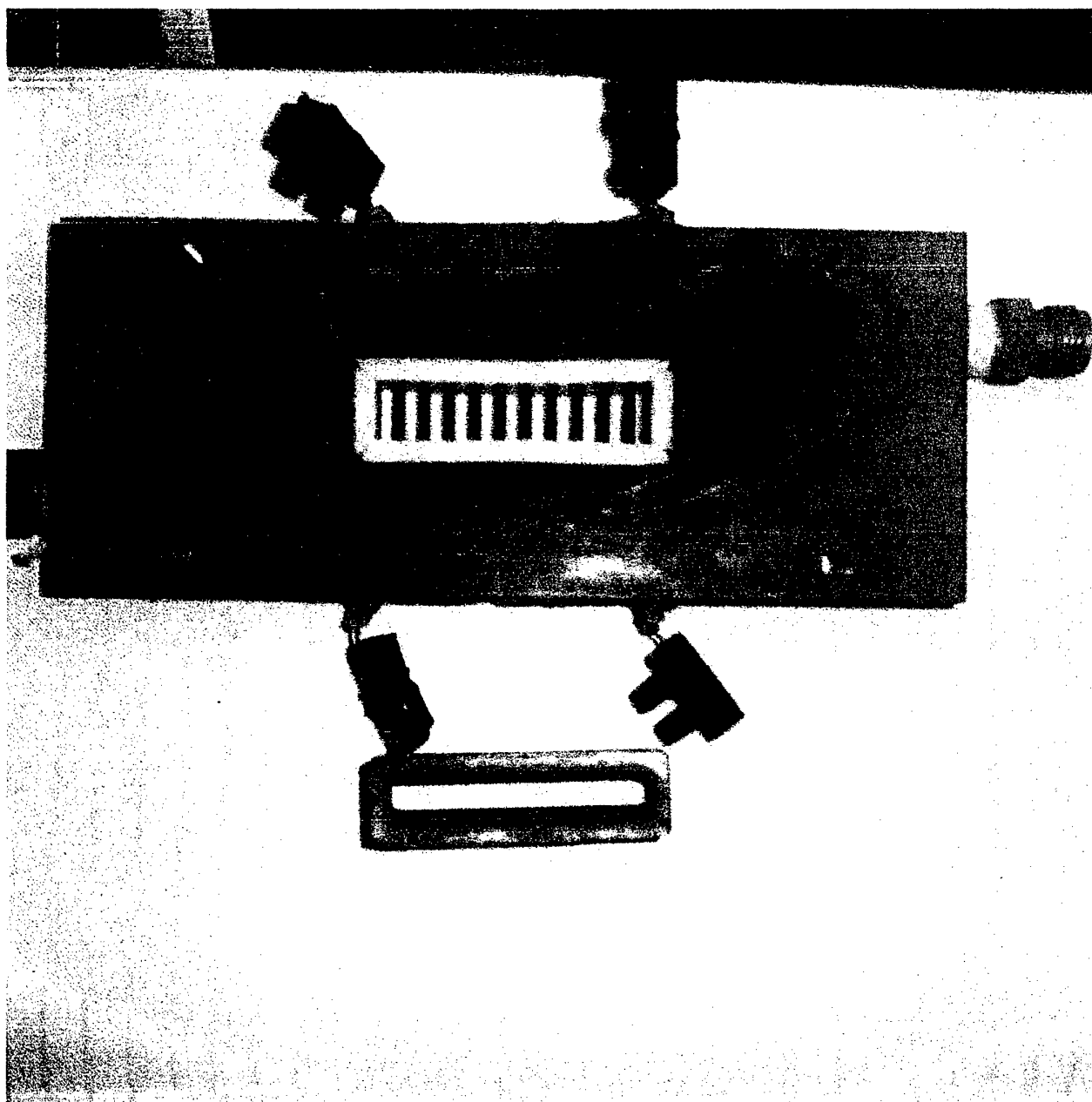
injection holes  
0.5 mm diameter



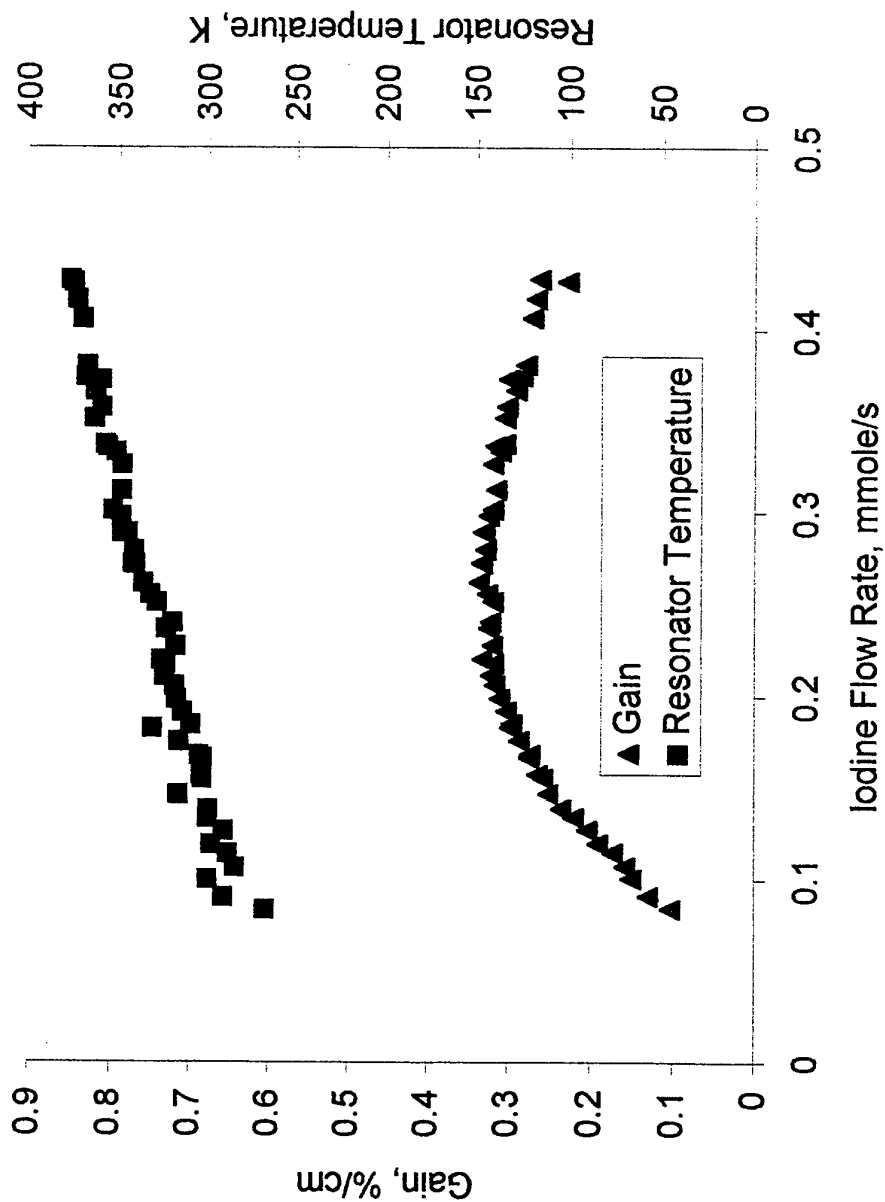
mirror







# Grid nozzle



Cl<sub>2</sub> 11.7 mmol

Yield 0.65

Utilization 0.92

Water 0.12

Sec. N<sub>2</sub> 1.36 mmol

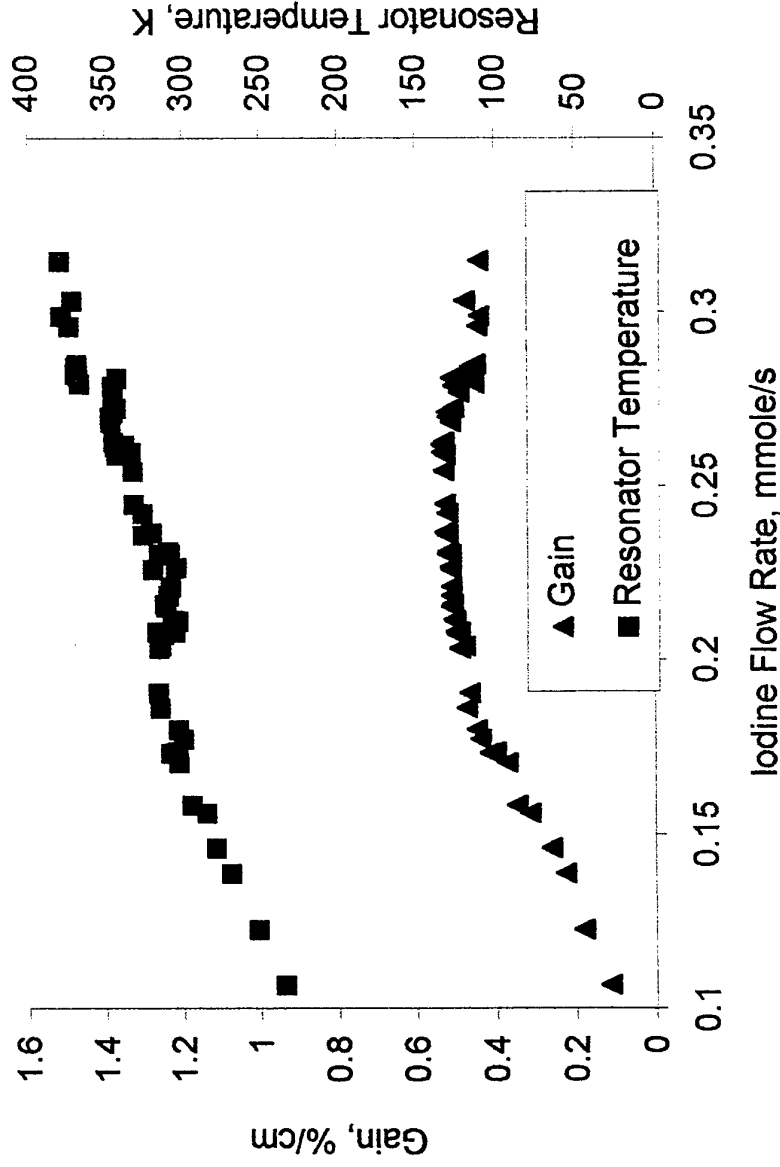
Stag. Temp. 340

Cold Res. Temp. 260

Res. Press. 1.4 Torr



# Slit nozzle #1



Cl<sub>2</sub> 11.7 mmole

Yield 0.6

Utilization 0.9

Water 0.12

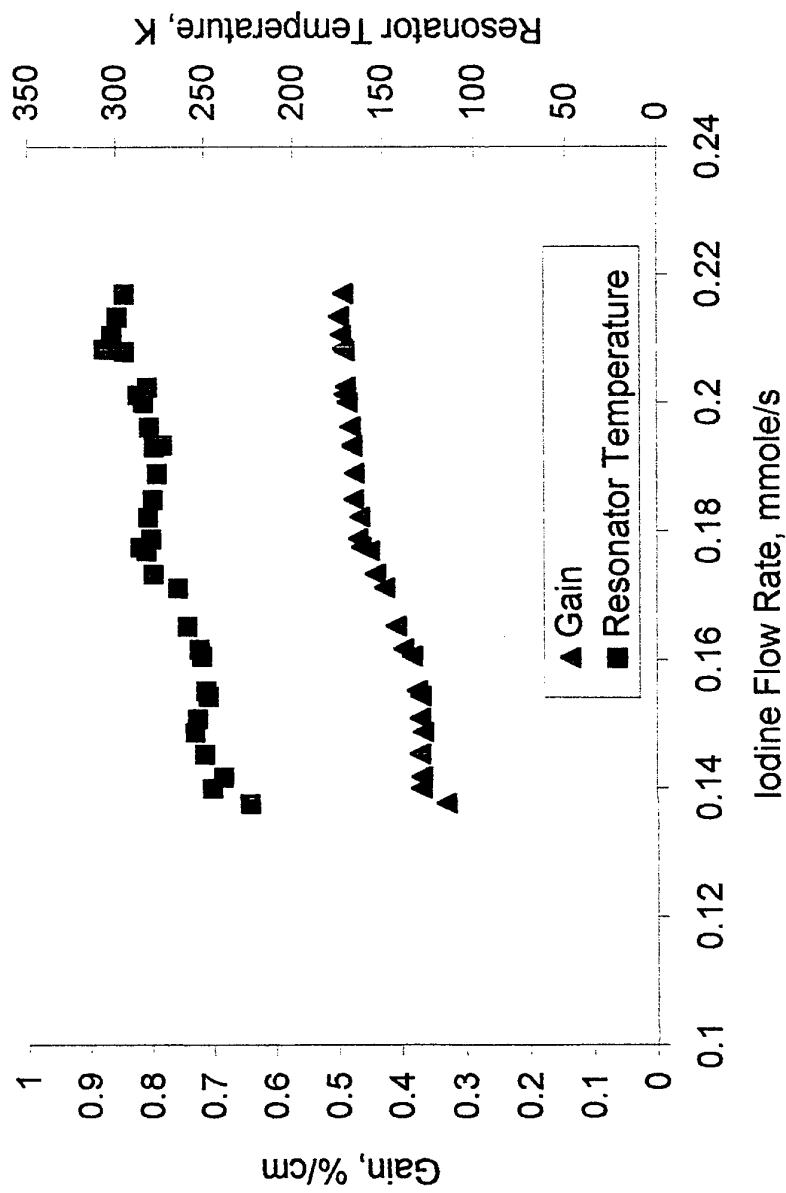
Sec. N<sub>2</sub> 2.5 mmole/s

Stag. Temp. 320 |

Cold Res. Temp. 260 |

Res. Press. 1.4 Torr

# Slit nozzle #1 (low resonator pressure)



Cl<sub>2</sub> 11.7 mmole/s

Yield 0.55

Utilization 0.9

Water 0.12

Sec. N<sub>2</sub> 2.5 mmole/s

Stag. Temp. 300

Cold Res. Temp. 190

Res. Press. 0.9 Torr

# Slit nozzle #1 (high Cl2 flow rate)

Cl2 19.5 mmole/s

Yield 0.55

Utilization 0.9

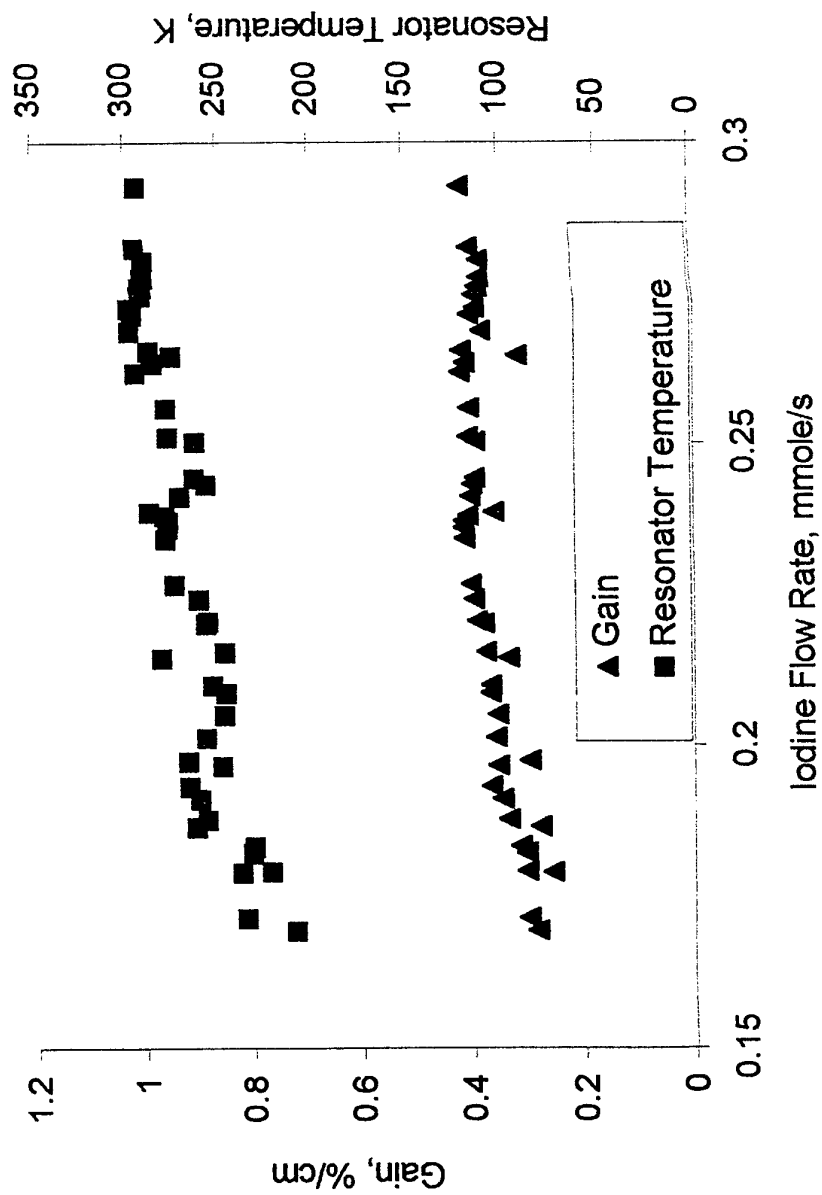
Water 0.12

Sec. N2 2.5 mmole/s

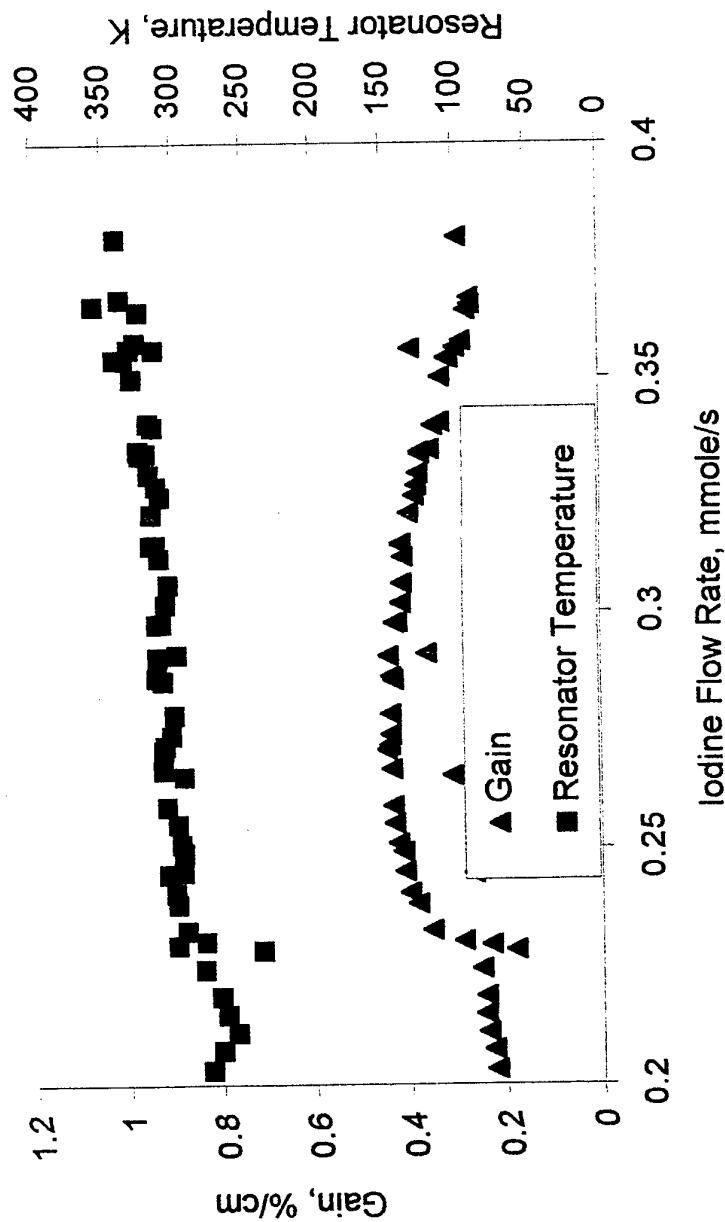
Stag. Temp. 320

Cold Res. Temp. 230

Res. Press. 1.55 Torr



# Slit nozzle #2



Cl<sub>2</sub> 11.8 mmole

Yield 0.55

Utilization 0.9

Water 0.12

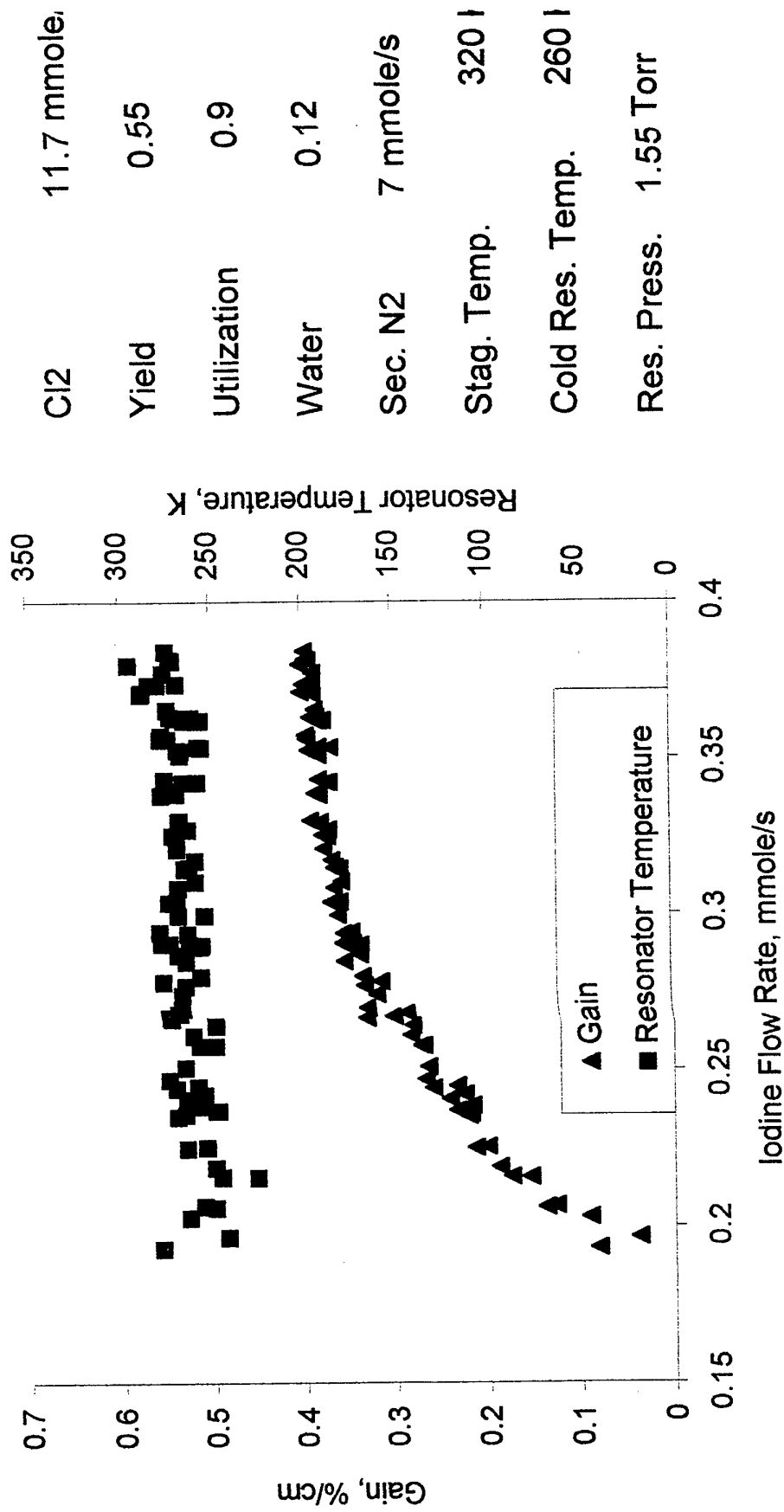
Sec. N<sub>2</sub> 4 mmole/s

Stag. Temp. 350

Cold Res. Temp. 260

Res. Press. 1.45 Torr

### Slit nozzle #3 (supersonic injection)



Cl<sub>2</sub> 11.7 mmole,

Yield 0.55

Utilization 0.9

Water 0.12

Sec. N<sub>2</sub> 7 mmole/s

Stag. Temp. 320 K

Cold Res. Temp. 260 K

Res. Press. 1.55 Torr

## Conclusions

1. We measured gain and temperature in resonator of a supersonic COIL without primary buffer gas for different  $I_2$  injection scheme using diode laser based diagnostic.
2. Maximum gain of 0.54%/cm was obtained for a slit nozzle with transonic injection. The temperatures in the resonator correspond to the maximum gain was 320 K.
3. The gain is a non-monotonous function of  $I_2$  flow rate, whereas the temperature increases with increasing  $I_2$  flow rate.
4. The temperature in the resonator decreases with moving the injection point downstream.

# Results of COIL Gain Measurements

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K.Grünewald, F.Duschek, J.Handke

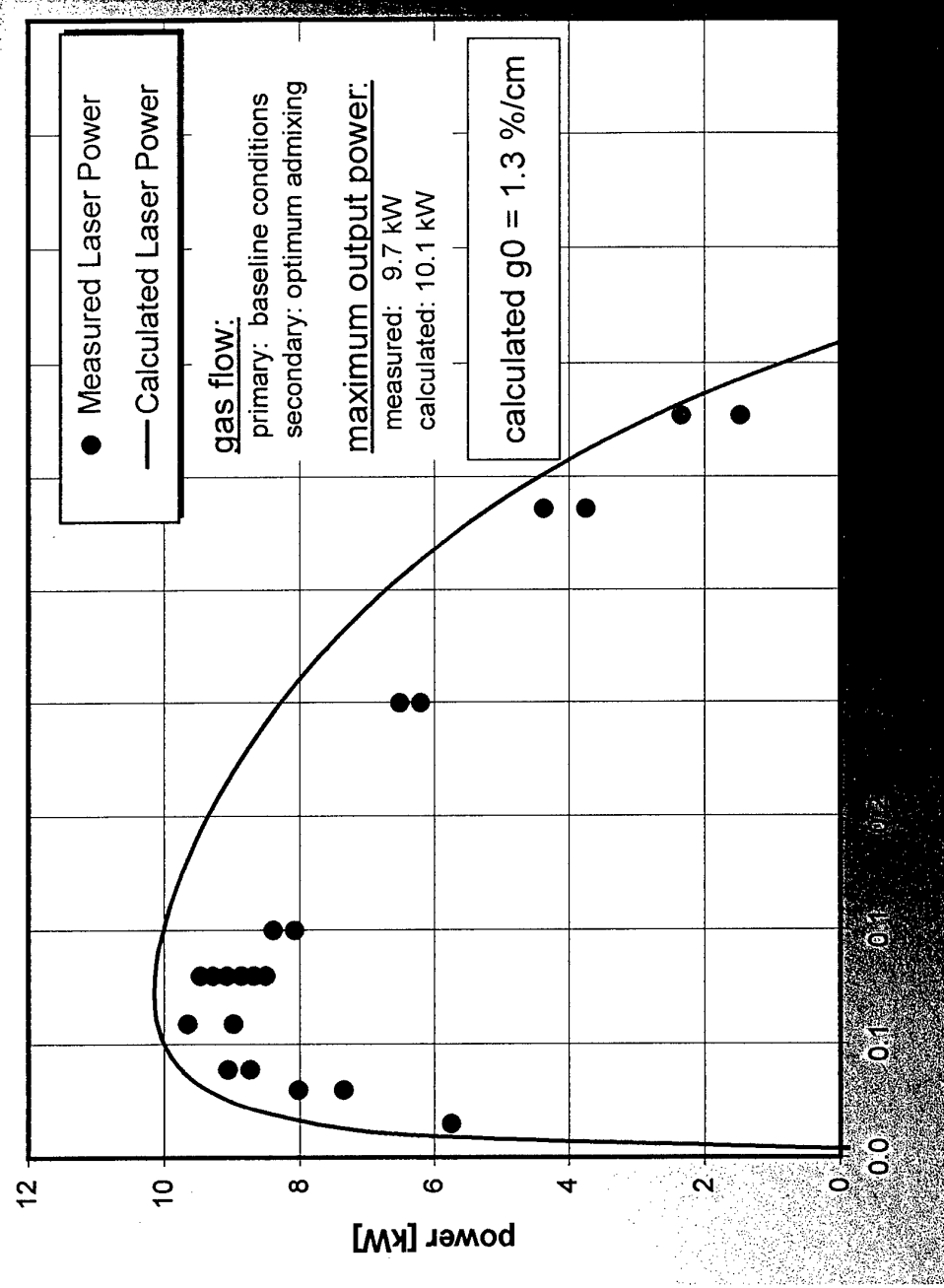
## Outline

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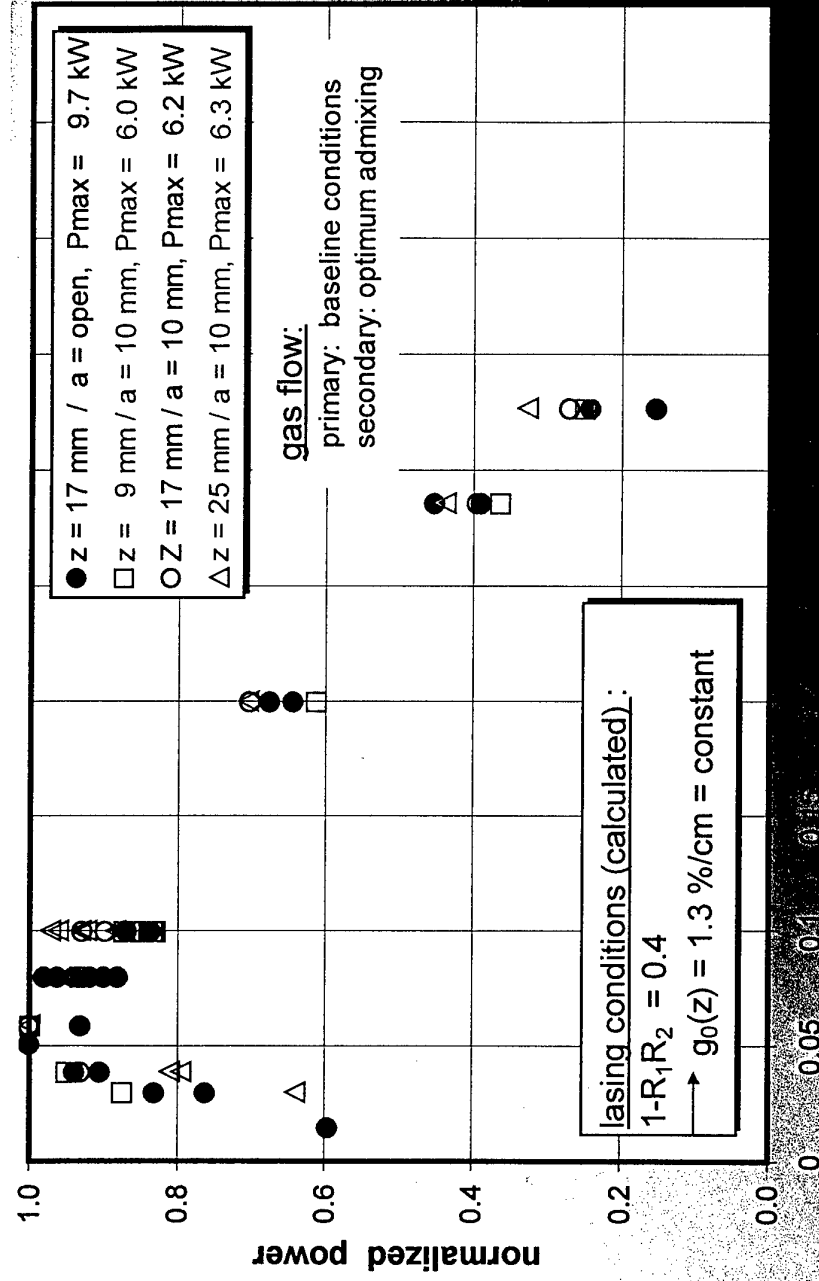
- Experimental Set-up
- Results of Stationary Measurements of SSG Coefficient and Temperature
- Local Scans of Gain and Temperature
- Effects of Gas Mixing Conditions on Small Signal Gain
- Localization of Dissociation Coefficient
- Summary



## Comparison of Experimental Data with Results of "COIL simplified Saturation Model"



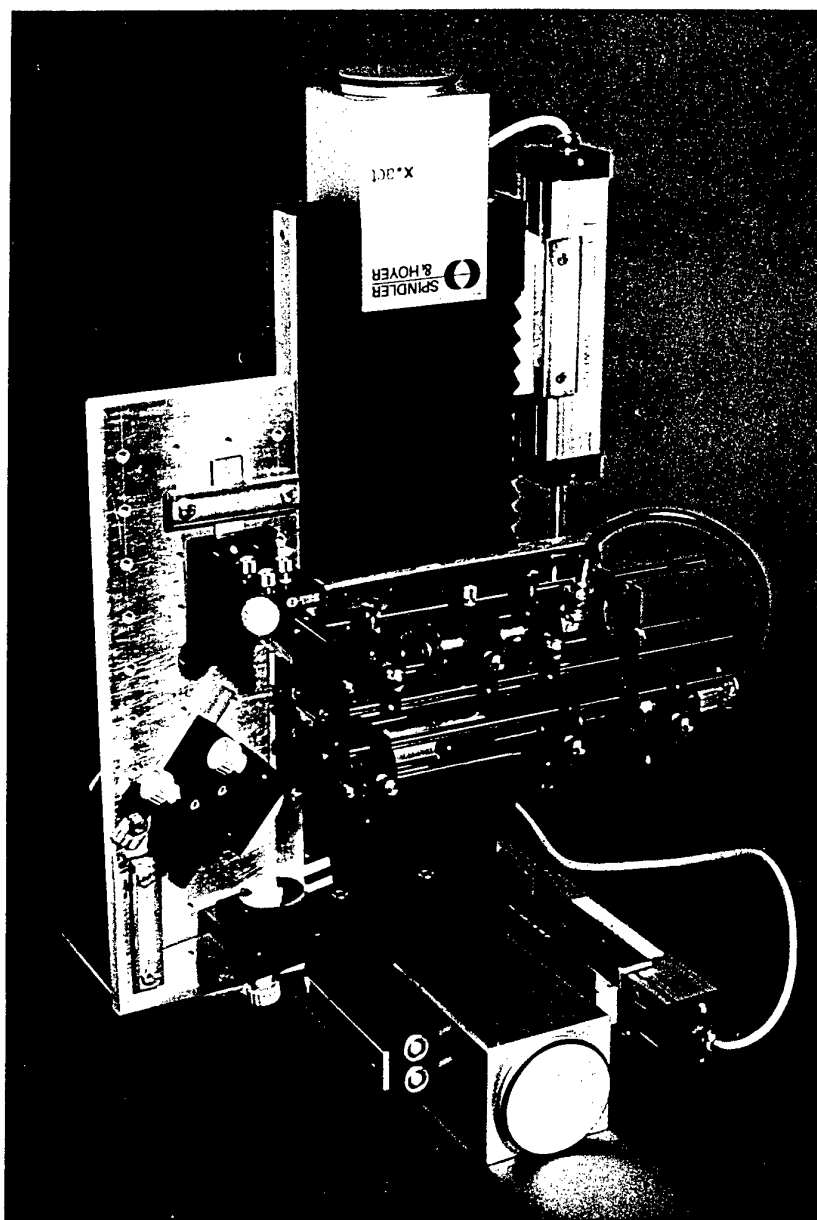
## Measured Output Power for Different Outcoupling Configurations



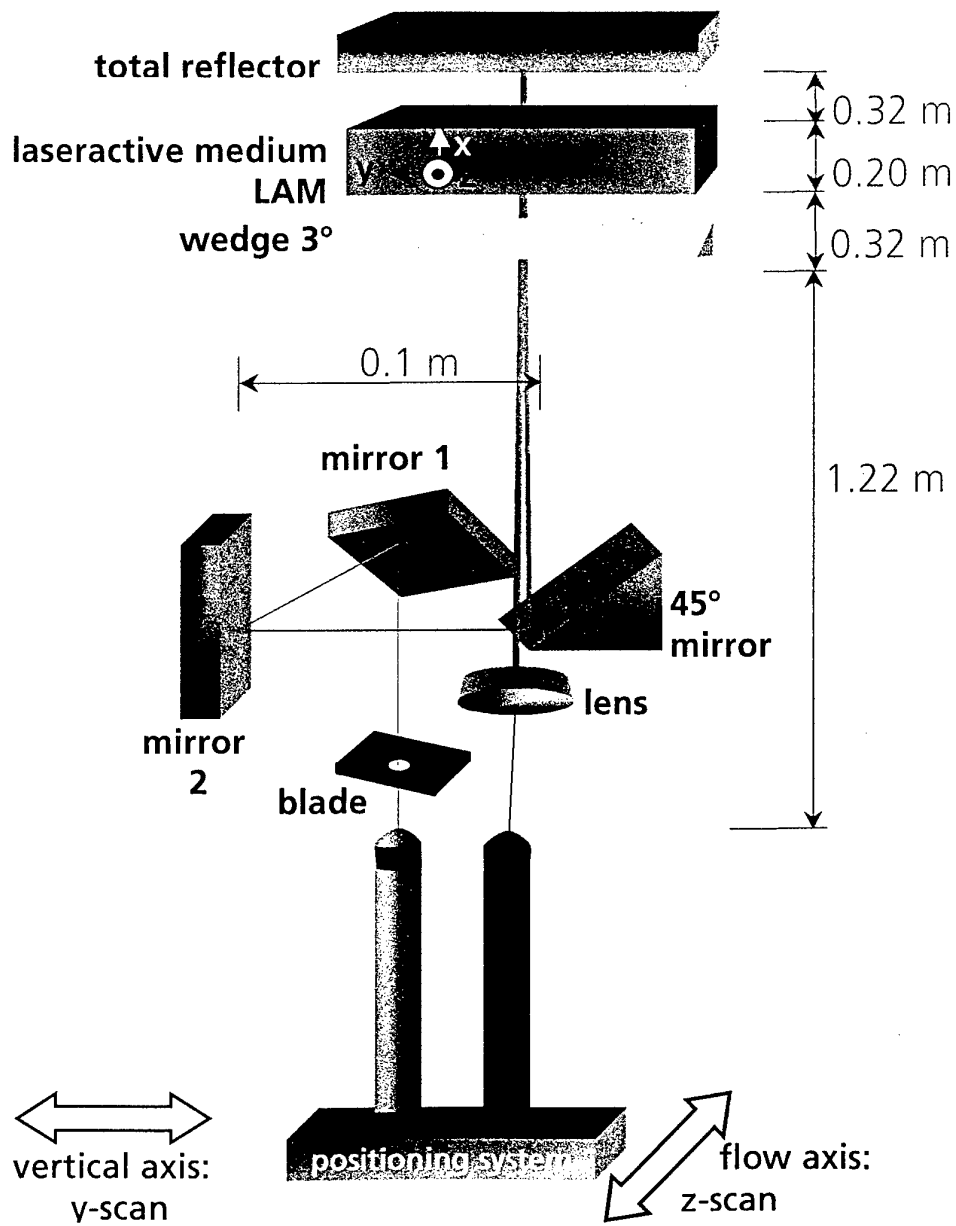
Deutsches Zentrum für Luft- und Raumfahrt e.V.

## Scanning Equipment with Emitter / Detector Unit

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## Experimental Set-up



## Spot Size and Position Definition

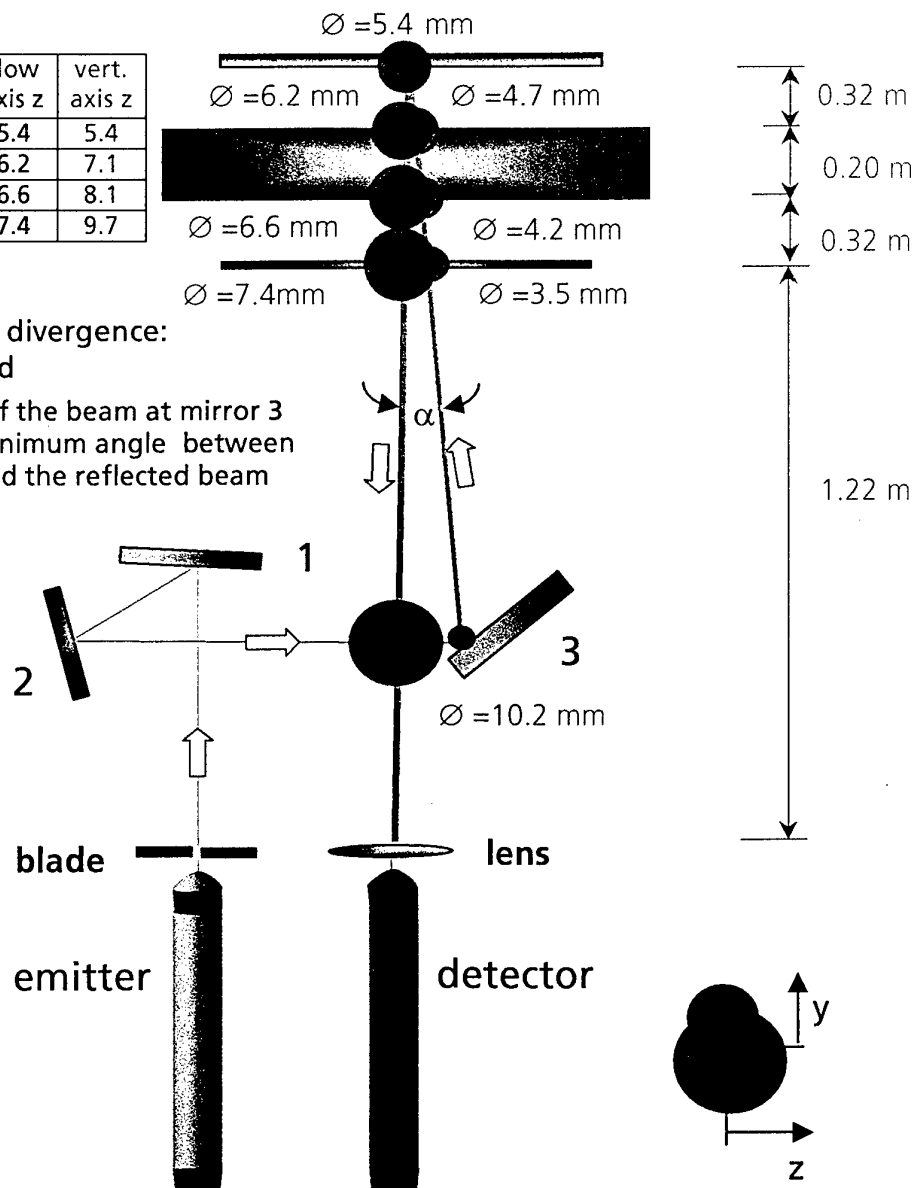
### spot size:

direction → ↓ position	flow axis z	vert. axis z
reflector	5.4	5.4
LAM (⇒mirror)	6.2	7.1
LAM (⇒wedge)	6.6	8.1
wedge	7.4	9.7

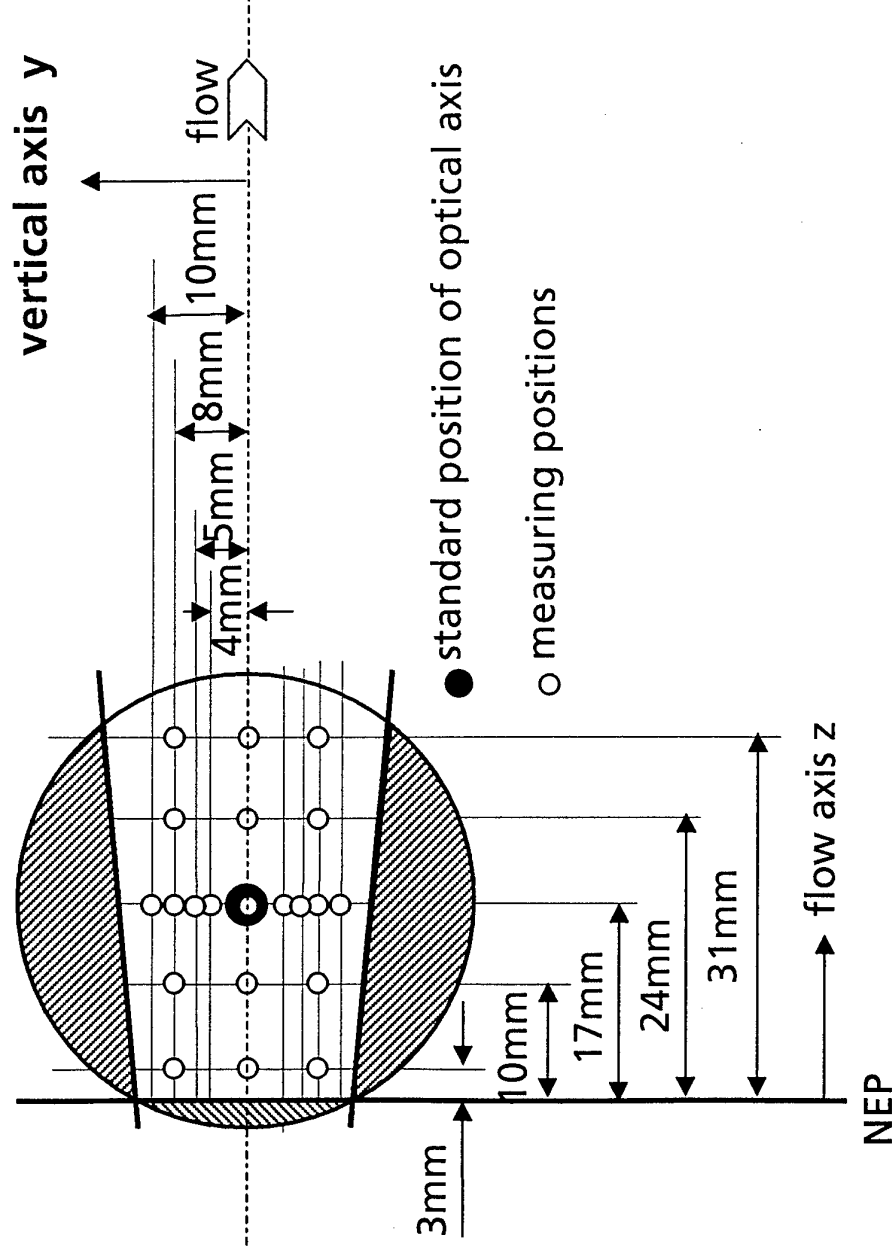
measured beam divergence:

$$\Theta = 2.3 \text{ mm} \cdot \text{mrad}$$

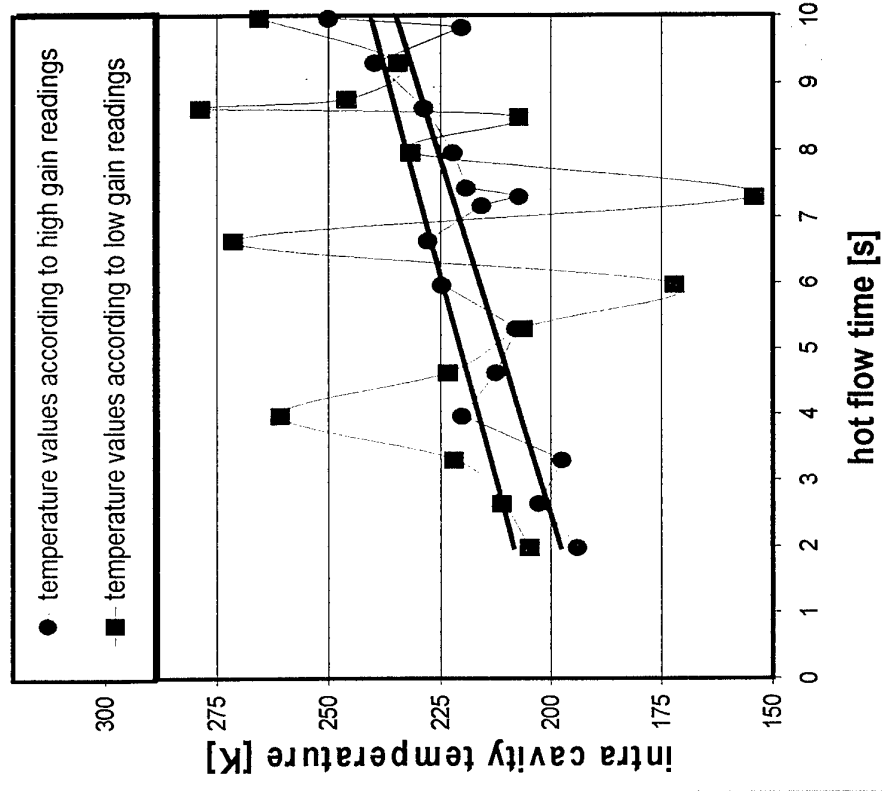
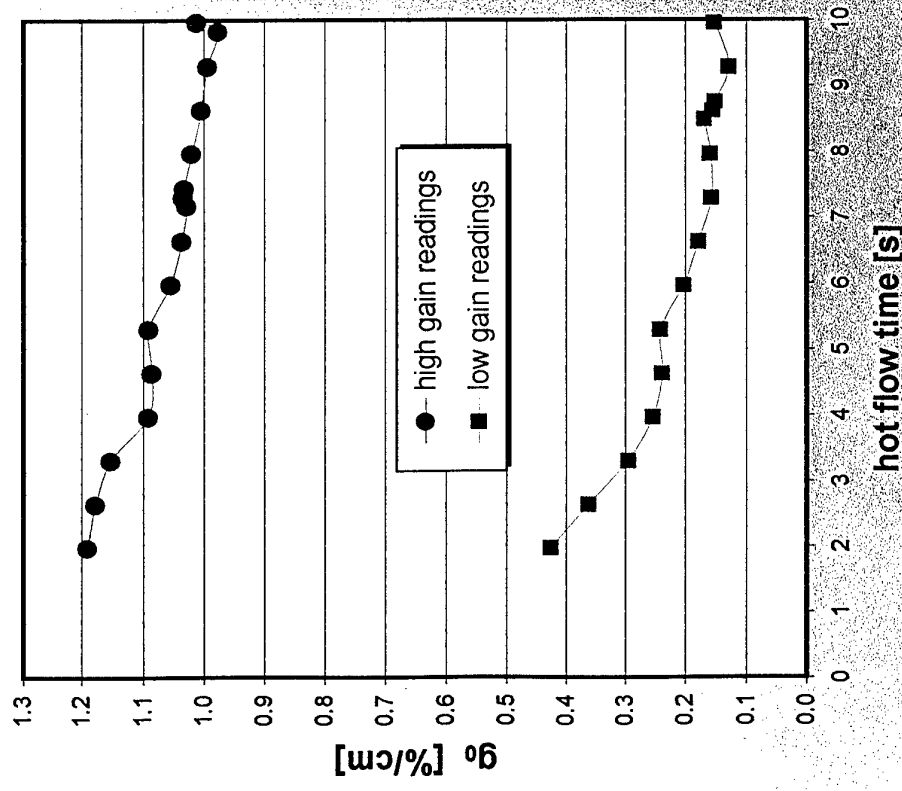
The dimensions of the beam at mirror 3 determine the minimum angle between the forwarded and the reflected beam



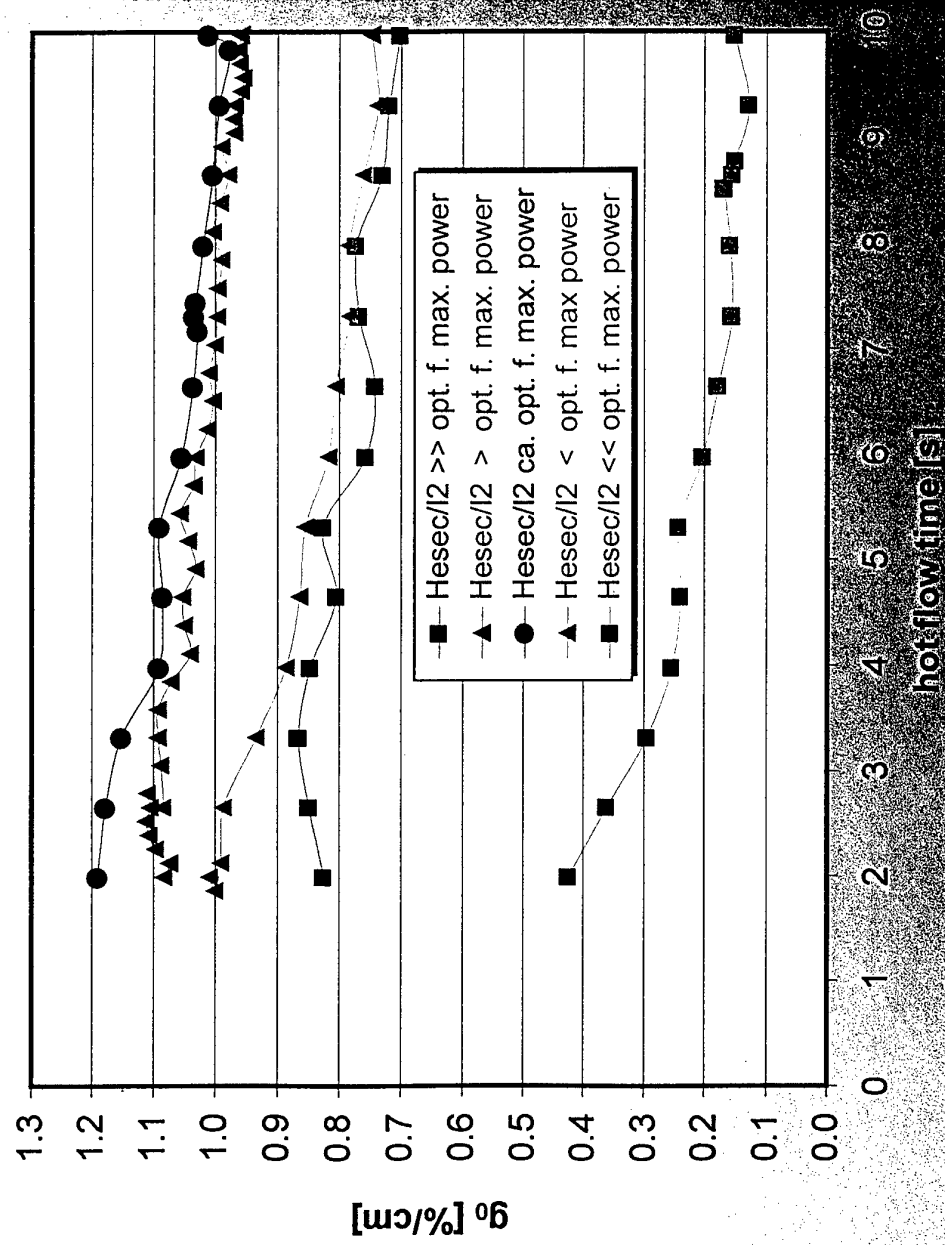
## Measuring Positions



# Readings of SSG Coefficient and Intra Cavity Temperature

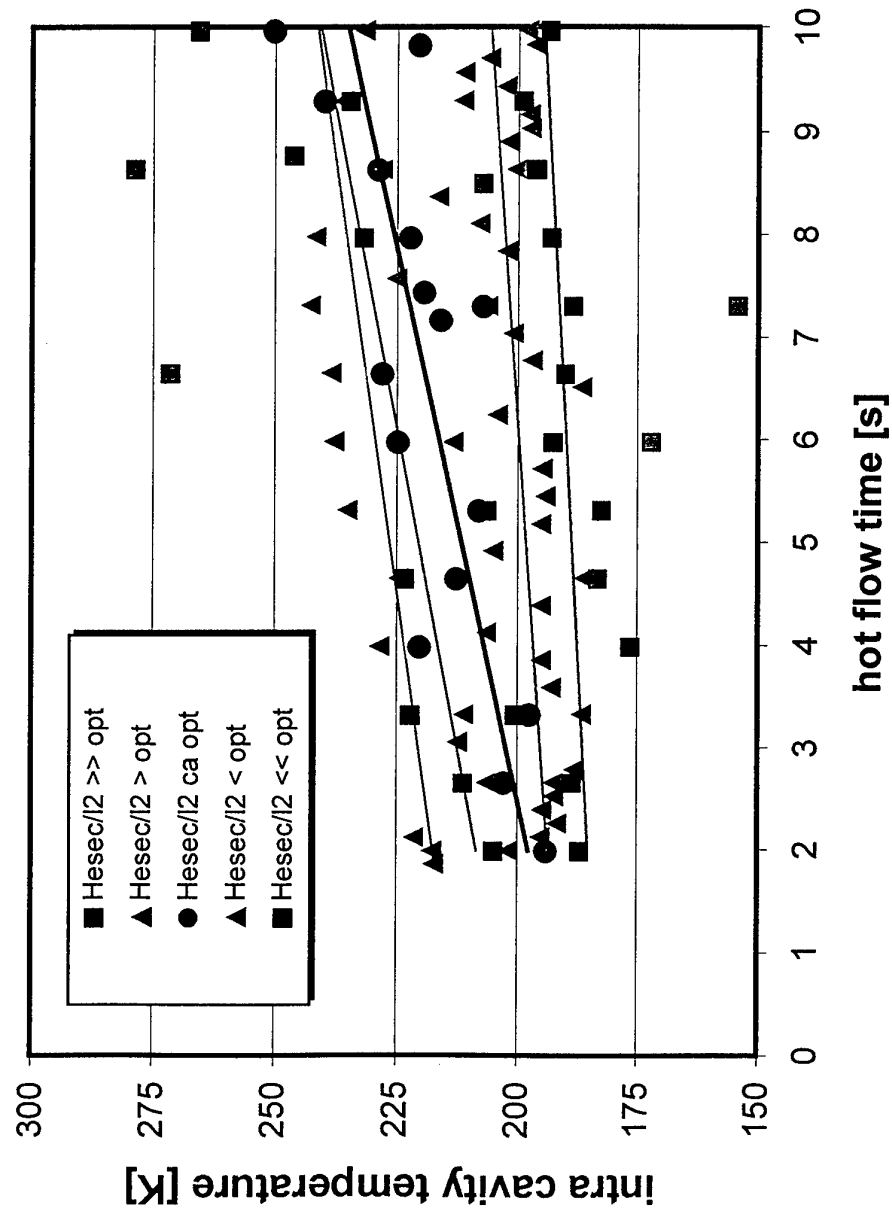


## Time Dependent Small Signal Gain Coefficient in the Position of the Optical Axis

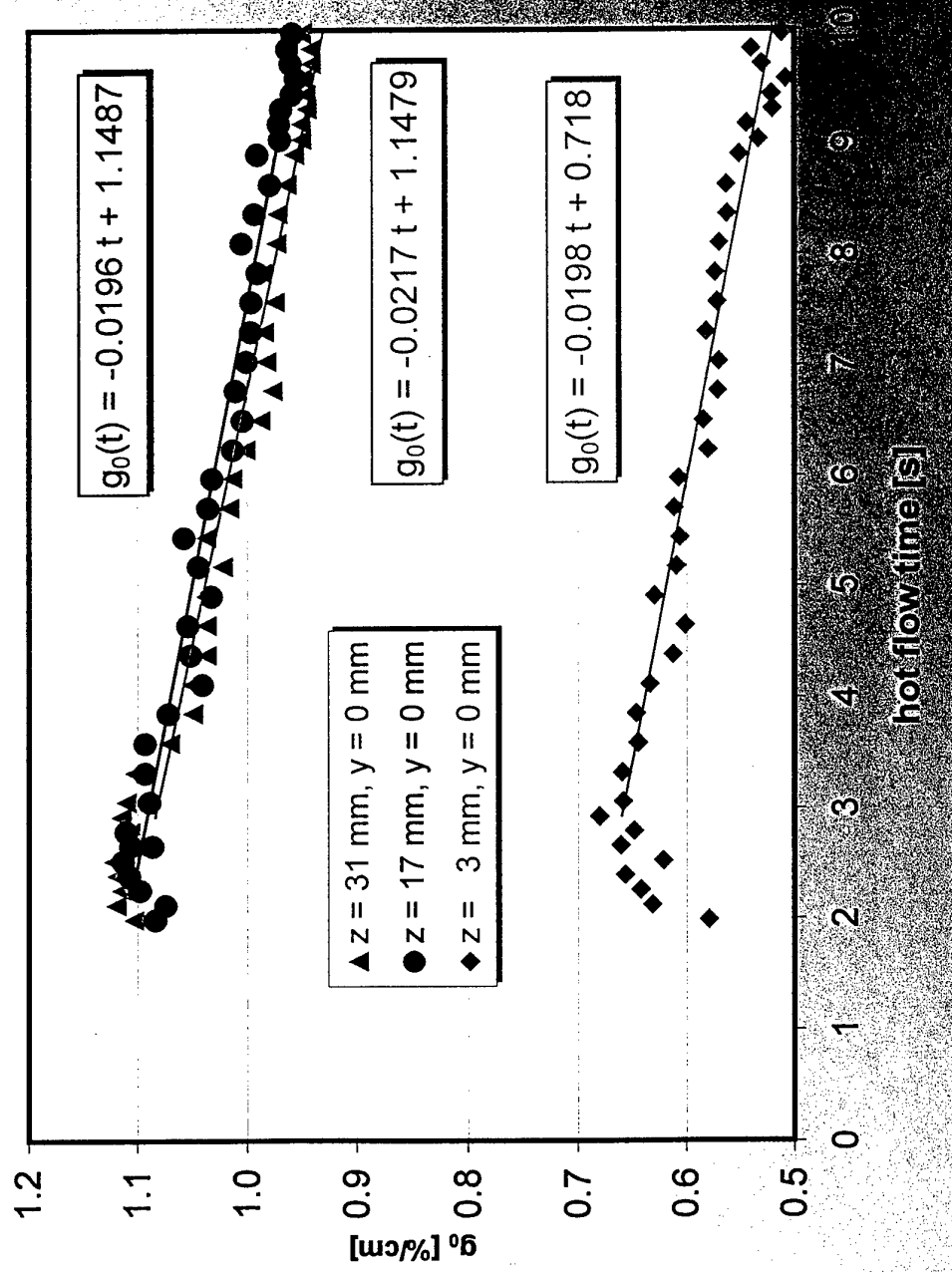




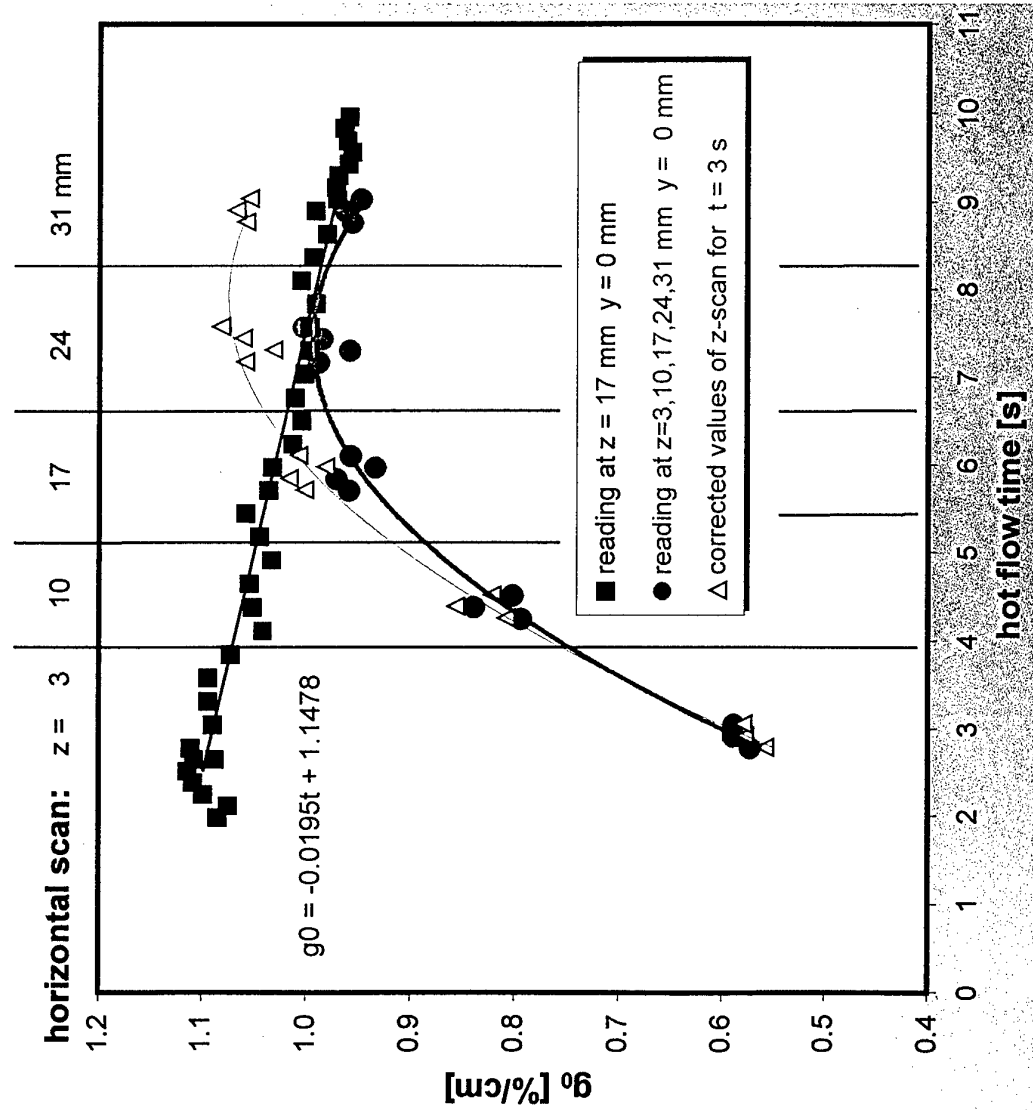
## Time Dependence of Temperature at the Position of the Optical Axis



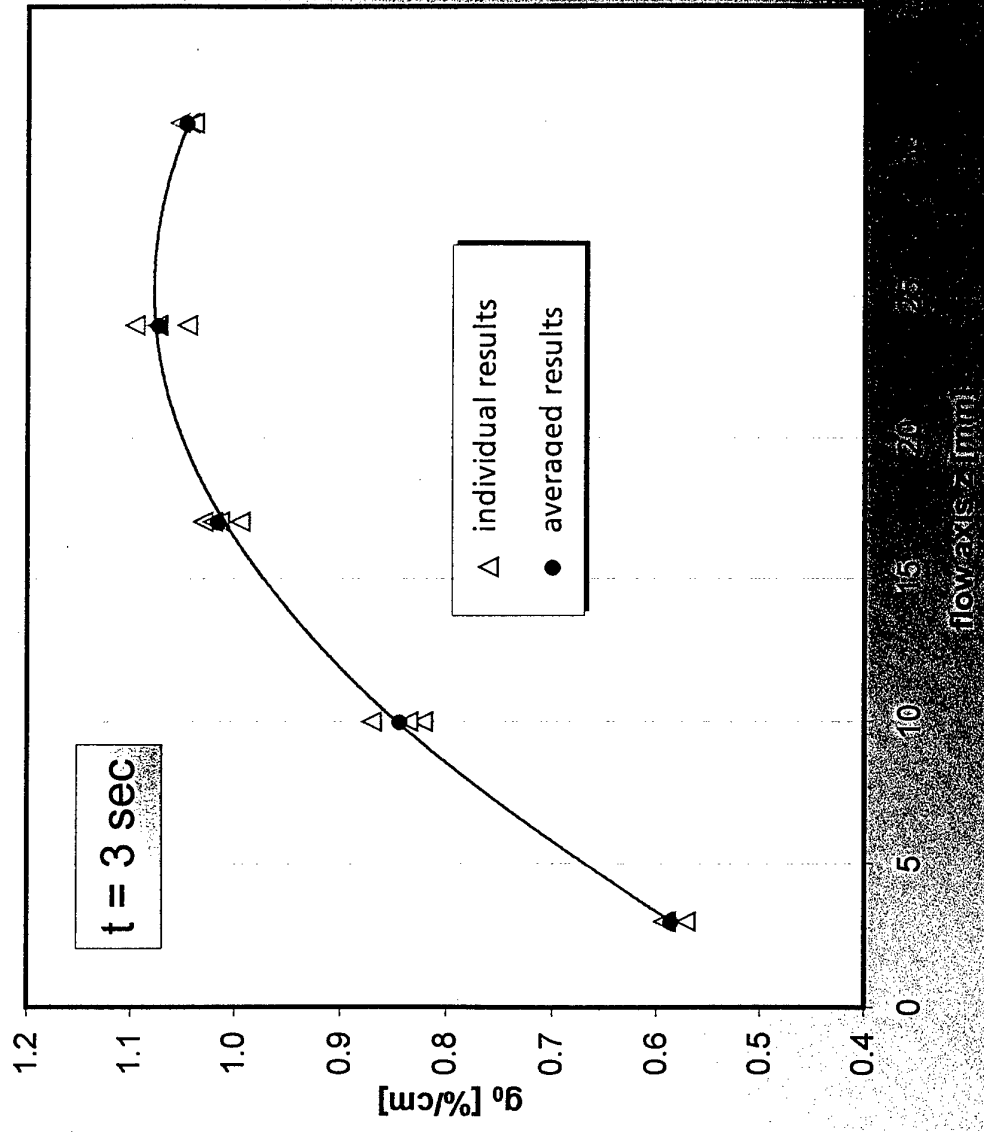
## Time Dependence of Small Signal Gain Coefficient



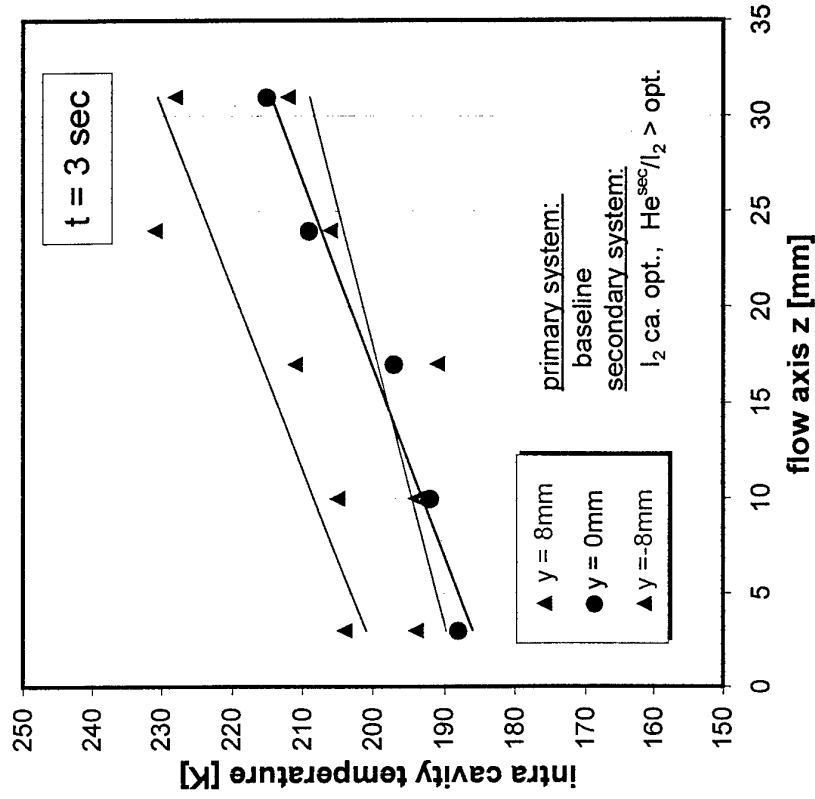
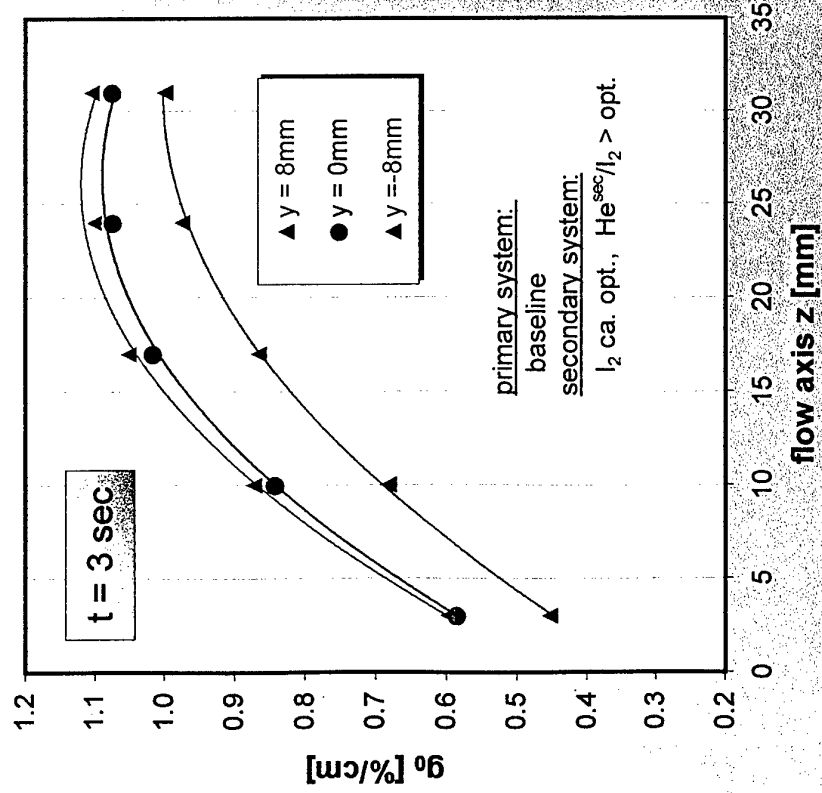
## Deconvolution of Time Dependence for Local Scans of $g_0$



## Local Dependence of the Small Signal Gain Coefficient

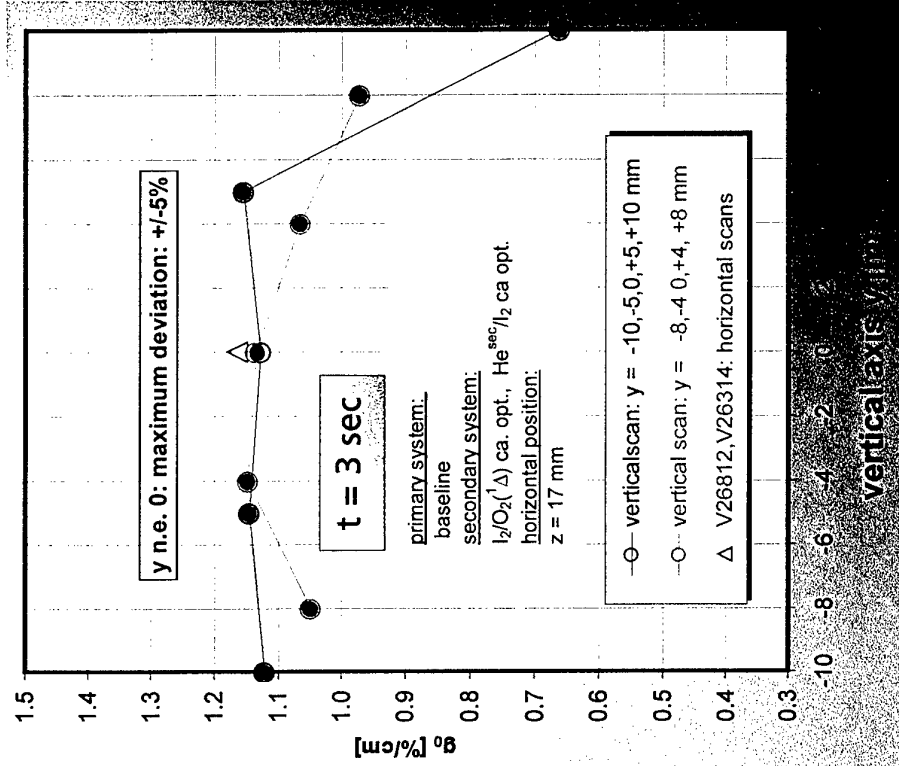
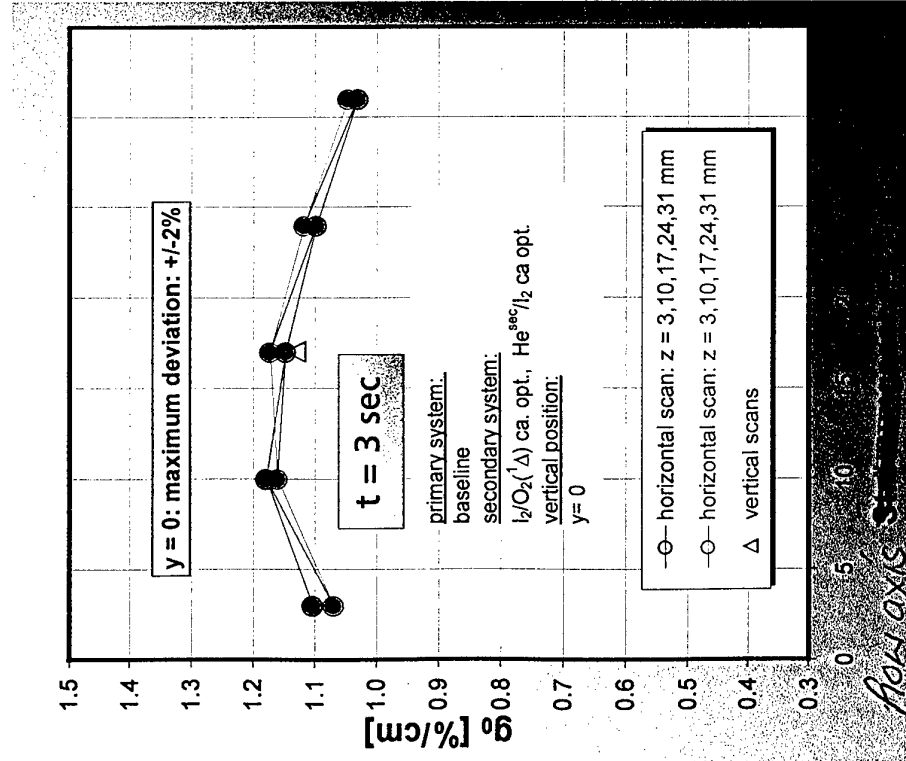


# Performance of SSG Coefficient and Intra Cavity Temperature Along the Flow Axis at Different Vertical Positions<sup>\*)</sup>

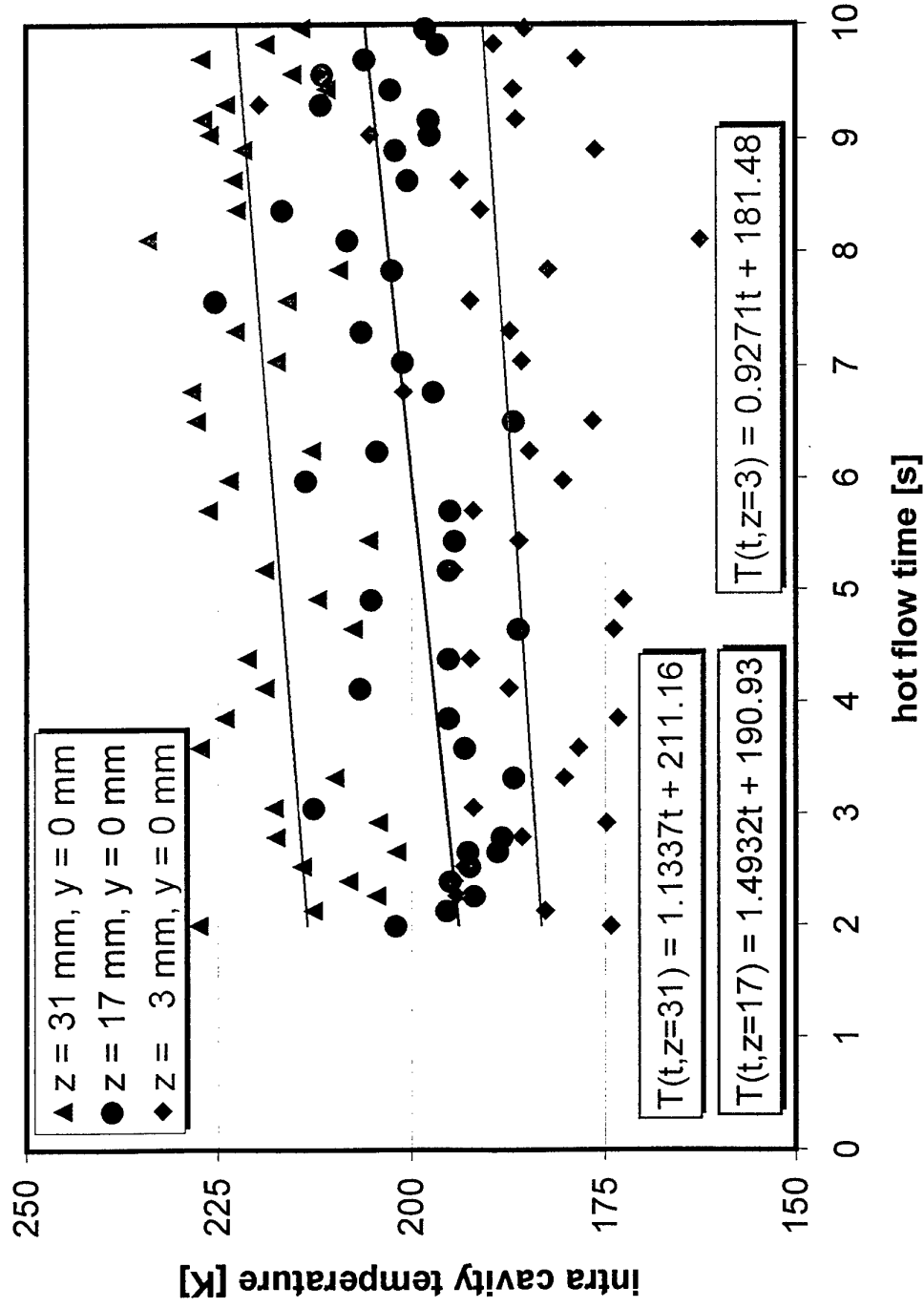


<sup>\*)</sup> unchanged operating conditions:  $\Gamma > \text{optimum for maximum power output}$

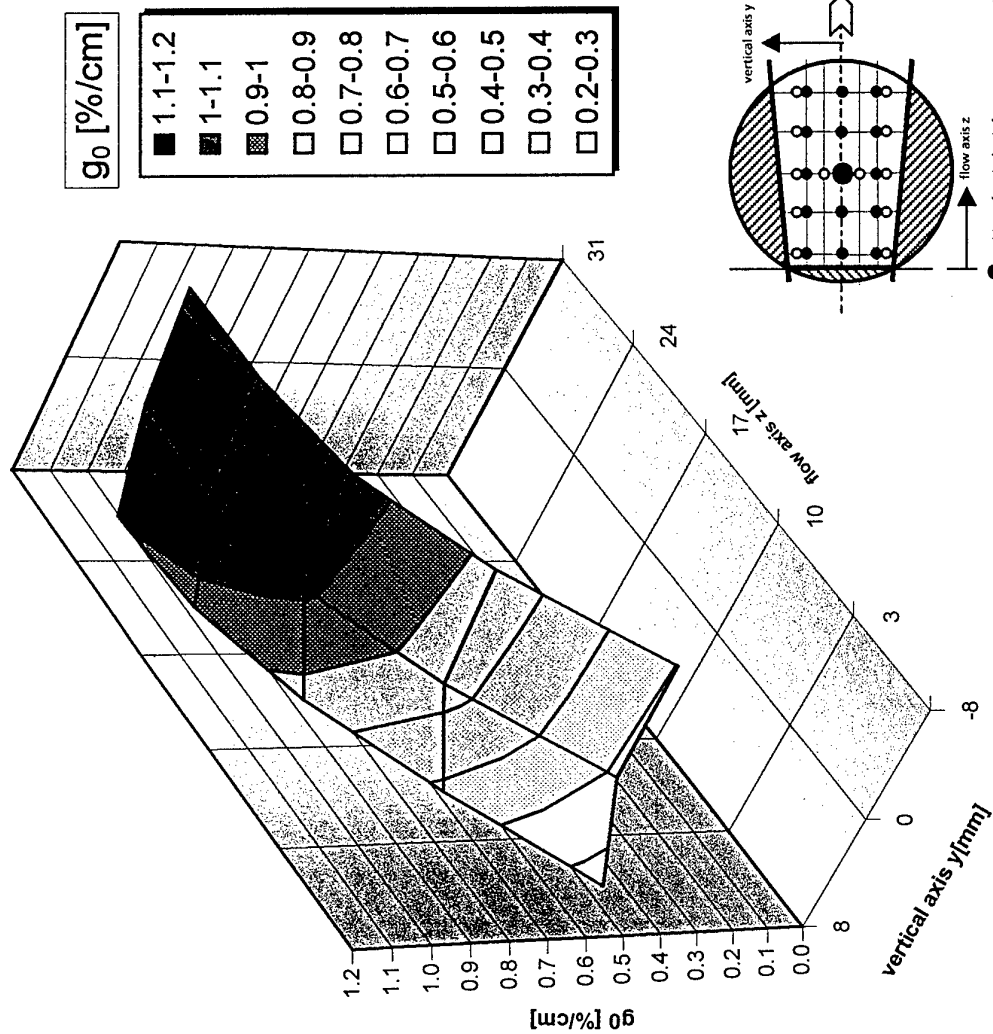
## Reproducibility



# Time Dependence of Intra Cavity Temperature

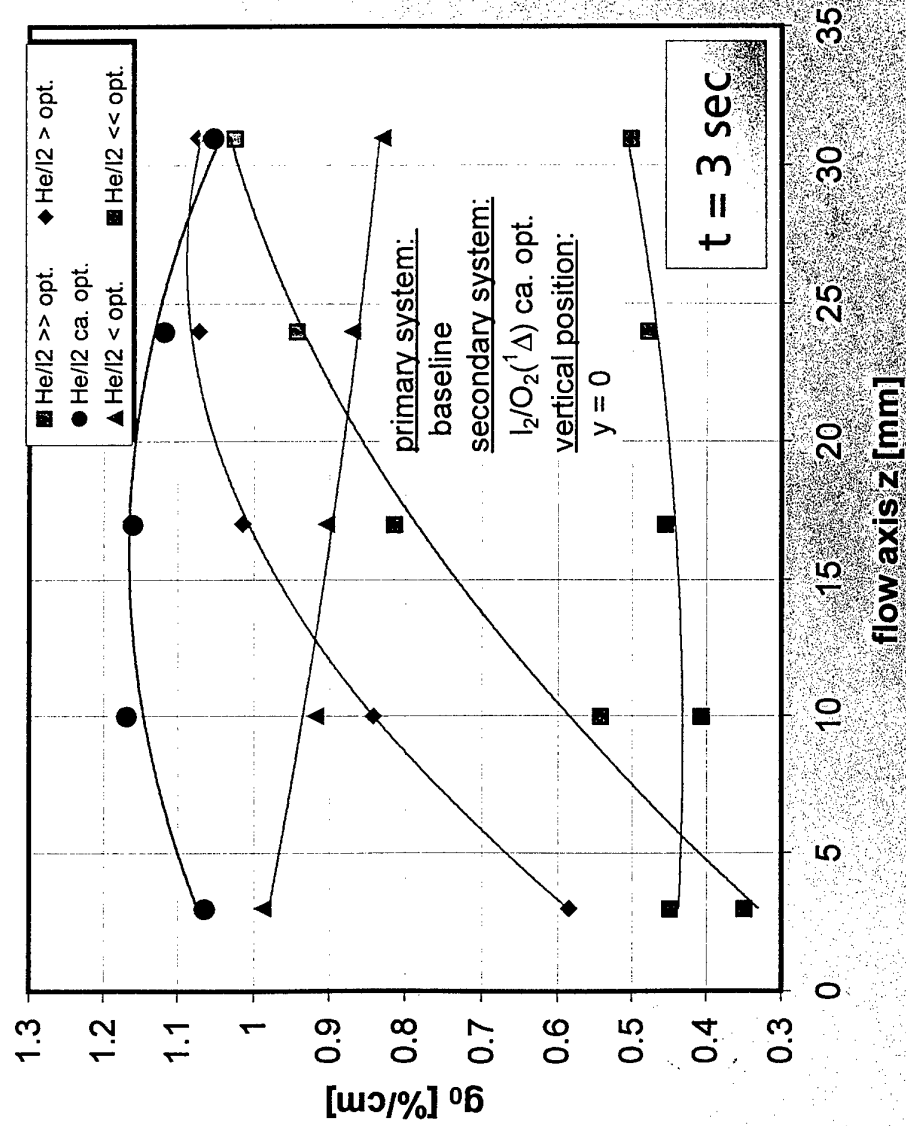


## 2D-field of SSG Coefficient

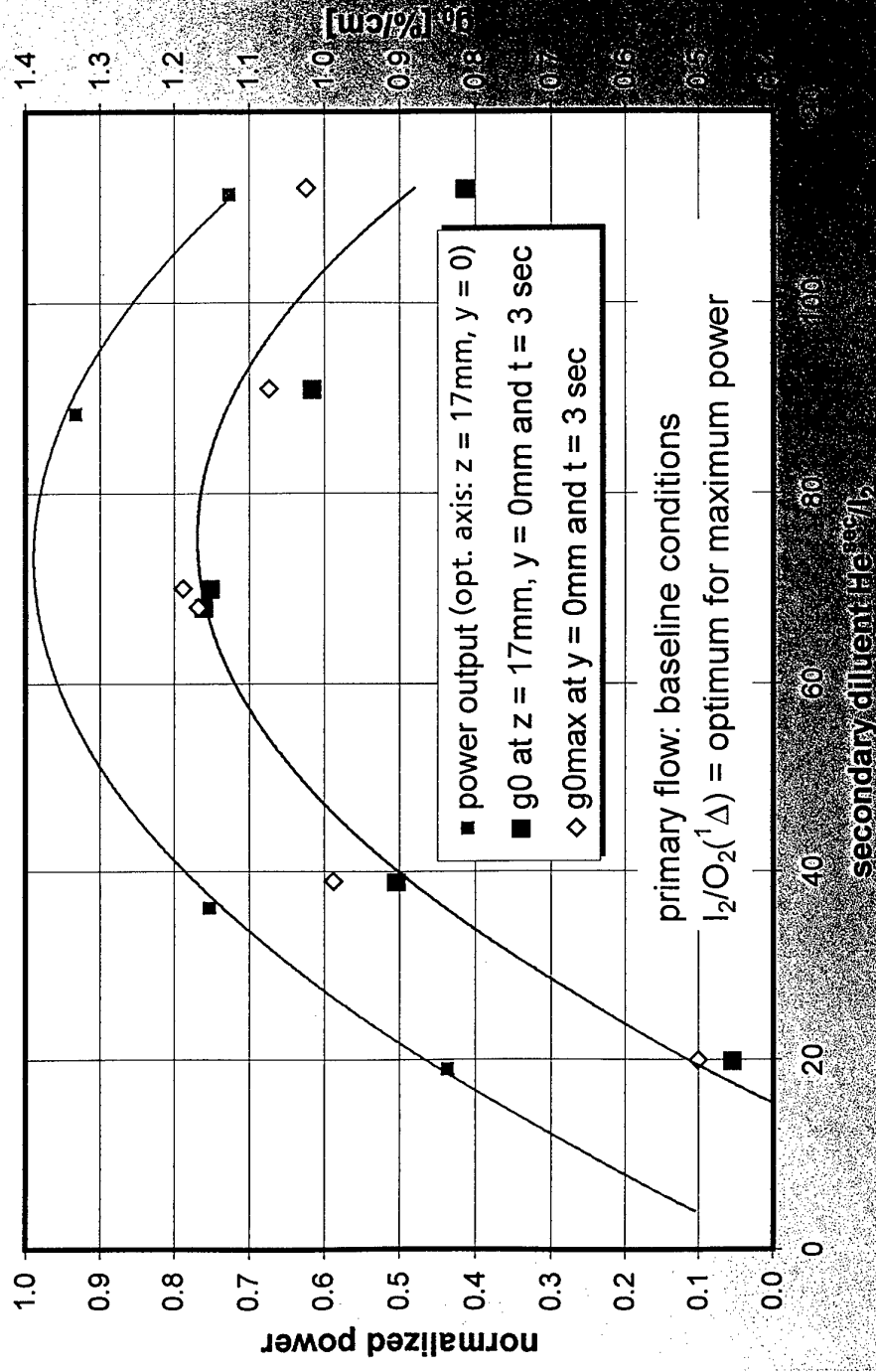




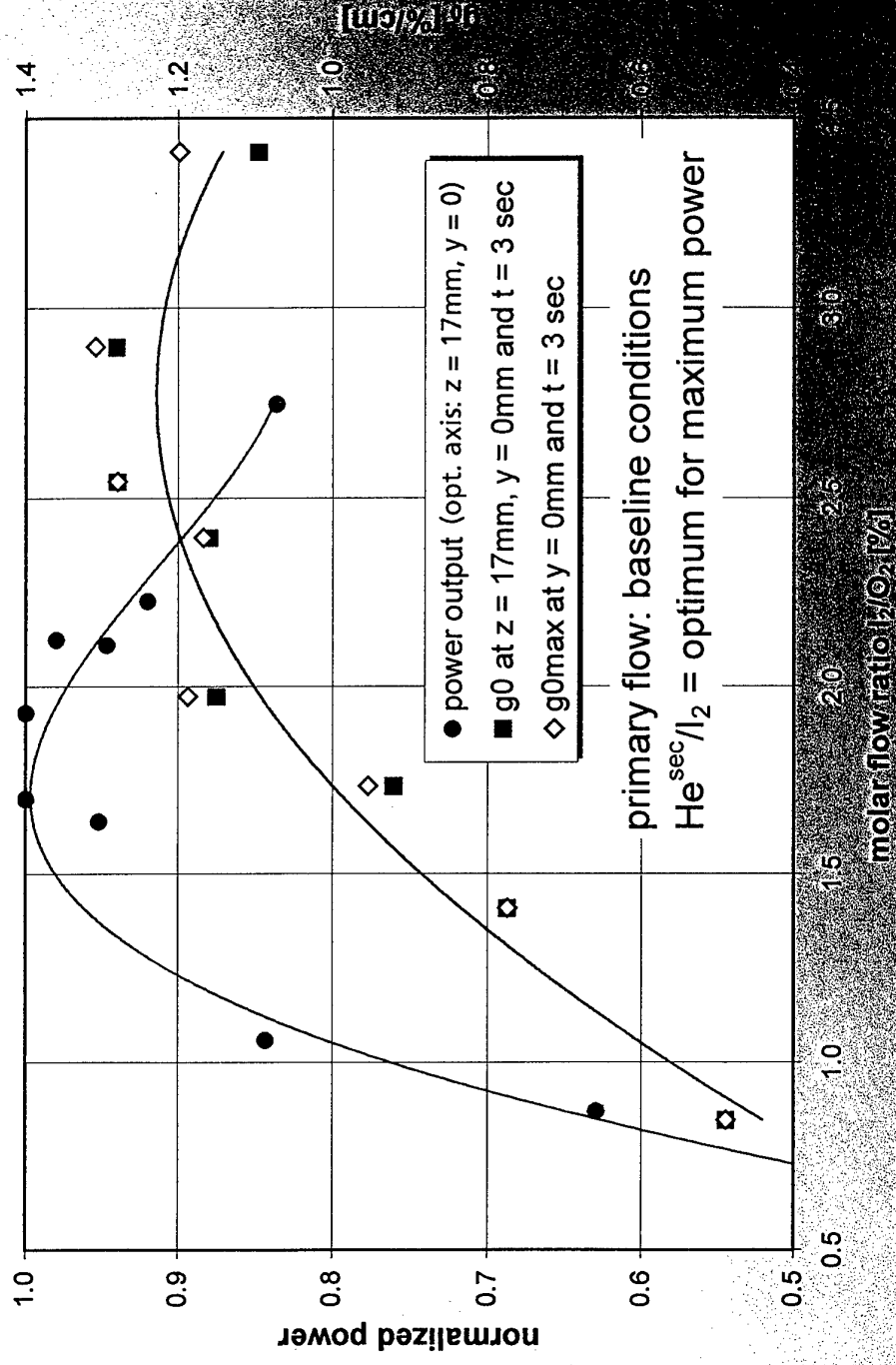
## Variation of Secondary Helium Flow



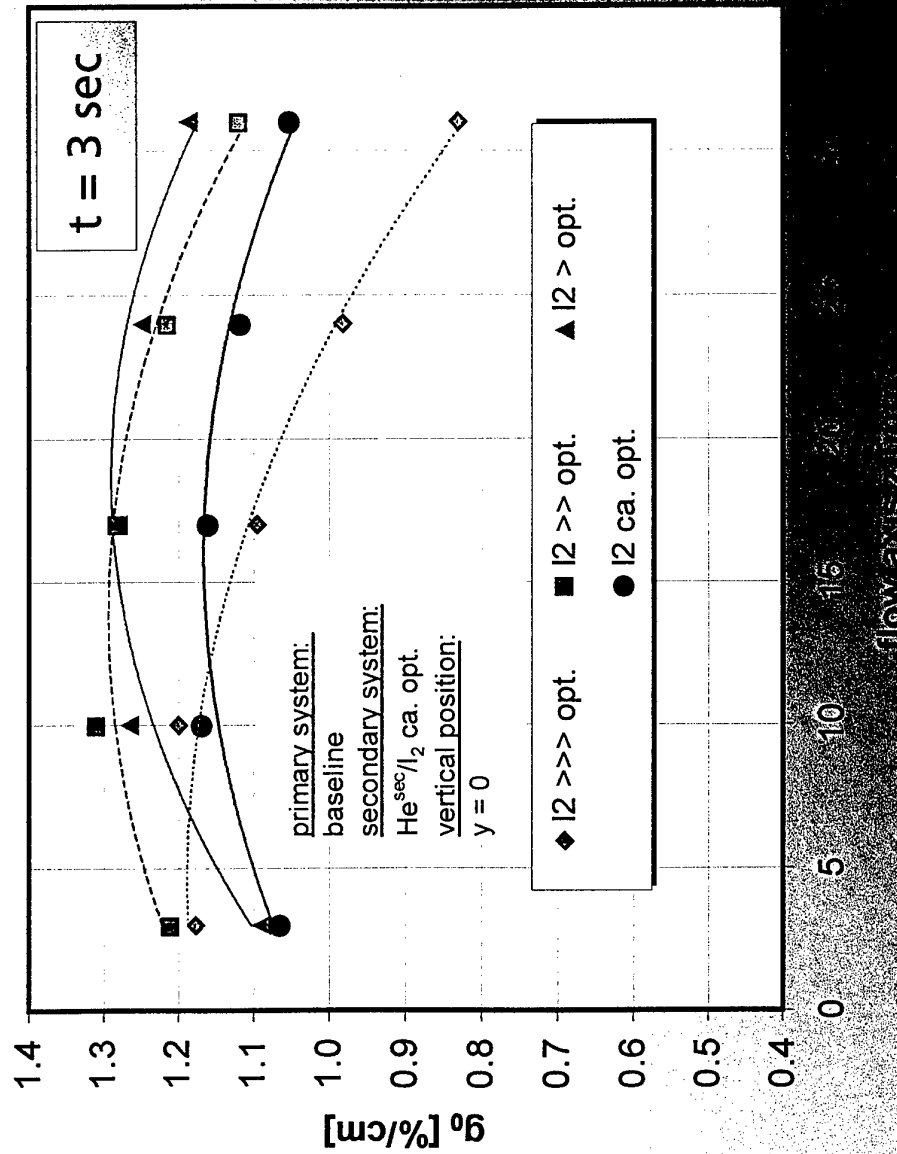
# Comparison of Maximum Laser Power and Maximum Gain Variation of Secondary Helium Flow



## Comparison of Maximum Laser Power and Maximum Gain Variation of Iodine Flow

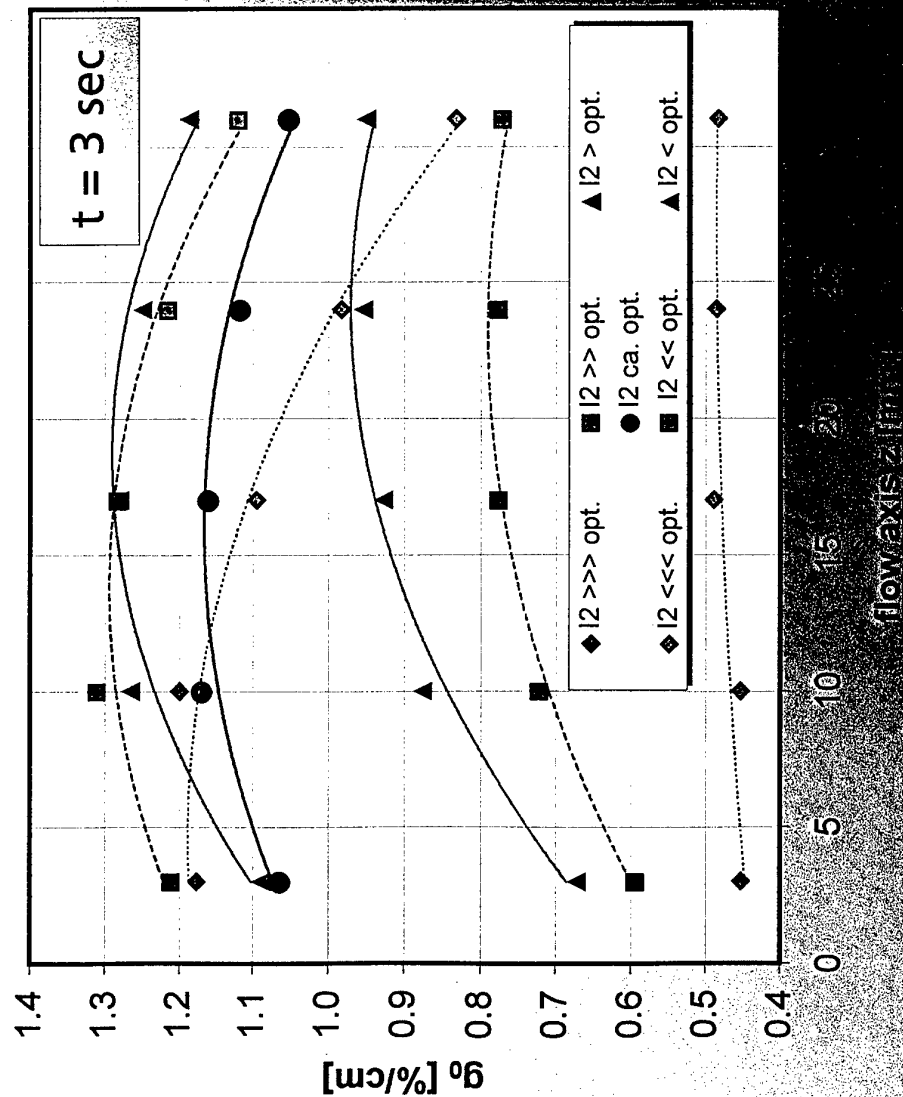


## Variation of Iodine Flow

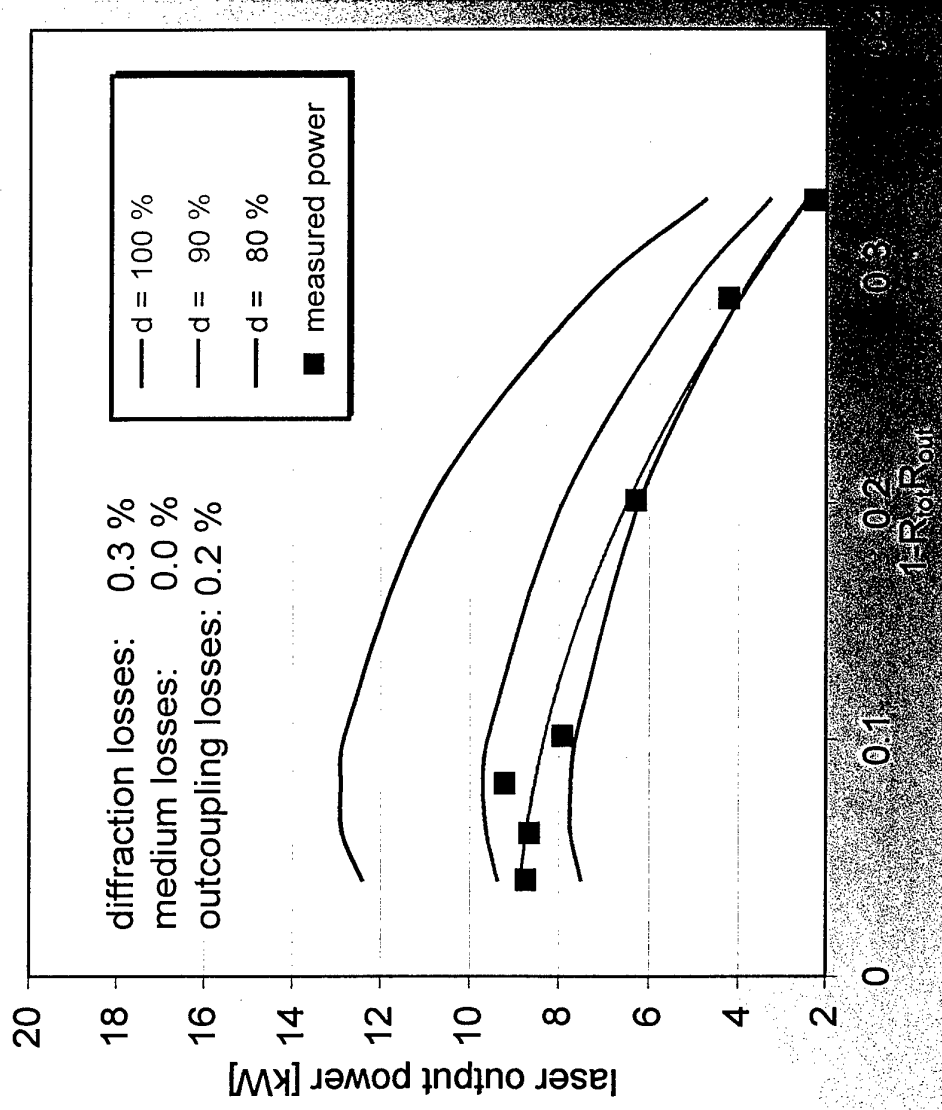


# Variation of Iodine Flow

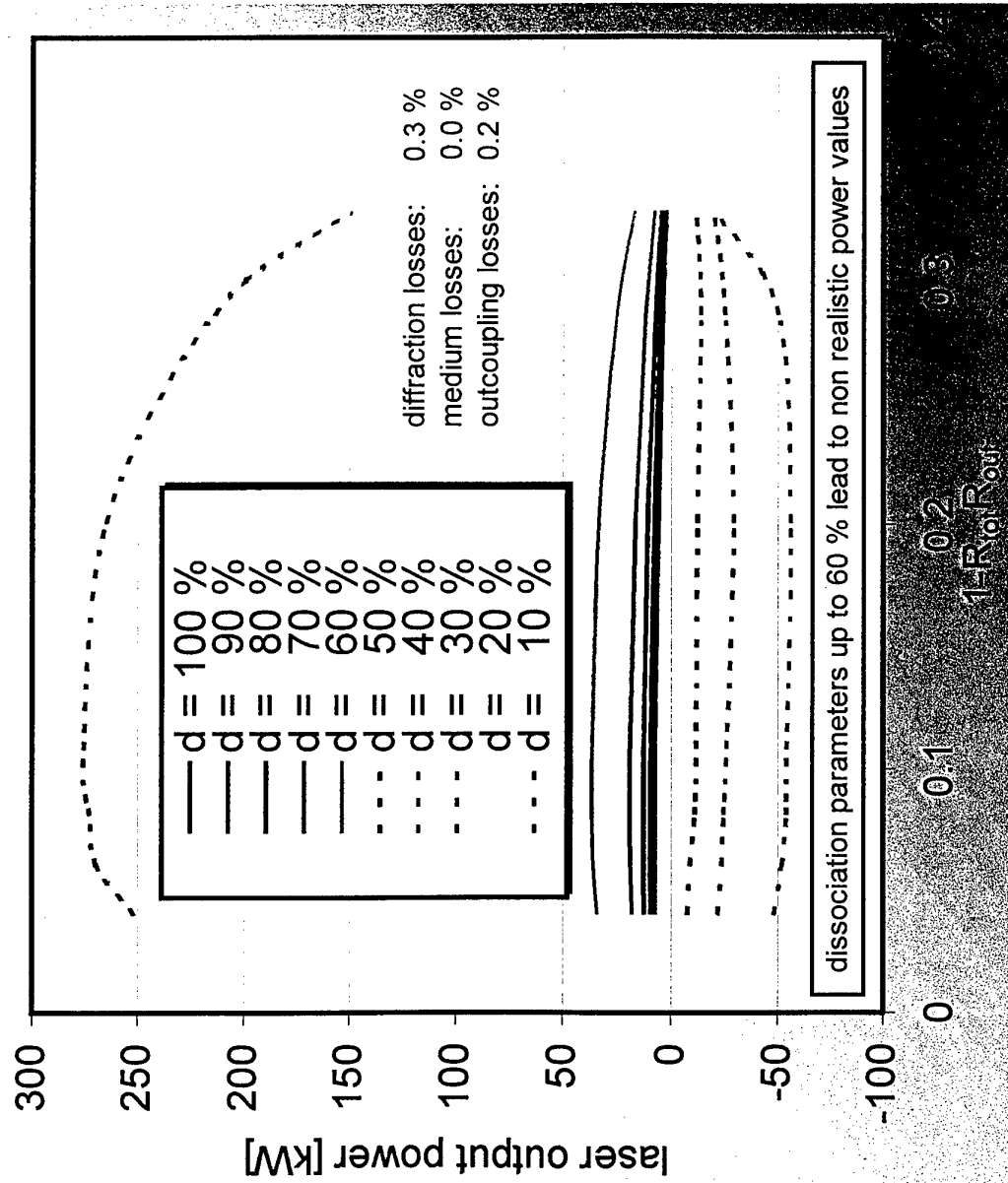
primary system:  
baseline  
secondary system:  
Hesec/I2 ca. opt.  
vertical position:  
 $y = 0$



## Comparison of Measured Laser Power and Calculated Results



# Calculated Laser Powers Dependent on the Dissociation Fraction



## Summary

---

- Good accordance between predicted and measured values of ssg coefficient
- Linear time dependence of ssg coefficient (negative gradient) as well as of intra cavity temperatures (positive gradient)
- Intra cavity temperatures measured in a range of 200 K and above
- Local dependence of small signal gain coefficient is determined by gas mixing

For optimum mixing conditions :

- Ssg Coefficient of about 1.2 %/cm, nearly constant along the flow axis.
- Dissociation coefficient in a range of 70 % - 90 %

Non optimum mixing conditions:

- Non constant local dependence of small signal gain coefficient
- SSg Coefficient (averaged over the cavity length) smaller than 1.2 %/cm  
only exception: increased iodine molar flow rate

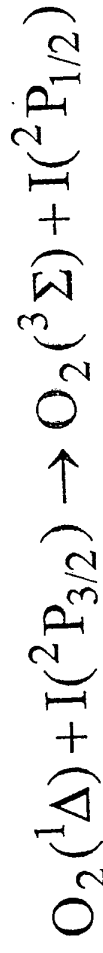
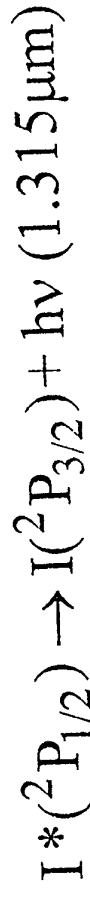


# **IODINE DISSOCIATION AND SMALL SIGNAL GAIN IN SUPERSONIC COILS**

**B. D. Barmashenko, D. Furman, E. Bruins and S. Rosenwaks**

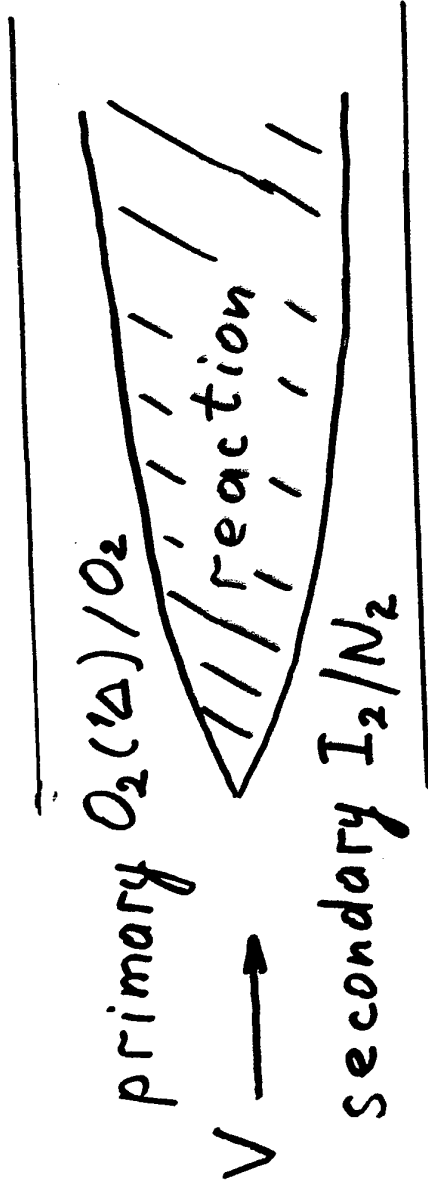
**Department of Physics, Ben-Gurion University of the Negev,  
Beer-Sheva 84105, Israel**

## COIL



Measurements: dependencies of the gain  $g$  and temperature  $T$  in the resonator on the iodine flow rate  $n\text{I}_2$  for different kinds of nozzles. addition  $Y$ ,  $U$ , water vapor fraction and  $T_{0i}$  were measured.

An analytical method for calculation of the iodine dissociation fraction  $F$  and the number  $N$  of  $\text{O}_2(^1\Delta)$  molecules lost in the region of iodine dissociation per  $\text{I}_2$  molecule.



$\eta_p, \eta_s$  — fractions of the primary or secondary flows present in the reaction zone

Relation between  $g$ ,  $F$  and the  $O_2(^1\Delta)$  yield  $Y$  at the optical axis:

$$g = \sigma_0 \left( \frac{300}{T} \right)^{1/2} \frac{p}{kT} \frac{nL_2}{n} F \frac{(2K_e + 1)Y - 1}{(K_e - 1)Y + 1}, \quad (1)$$

where  $\sigma_0 = 7.5 \times 10^{-18} \text{ cm}^2$  and  $K_e = 0.75 \exp(402/T)$  is the equilibrium constant of reaction (1).

Slit nozzle: right hand side of Eq. (1) is multiplied by

$$n/(n_p\eta_p + n_s\eta_s),$$

where  $n_p = (n\text{Cl}_2)_0 + n\text{H}_2\text{O}$  and  $n_s = n\text{N}_2 + n\text{I}_2$ ,  $\eta_p$  and  $\eta_s$  are the mixing efficiencies of the primary and secondary flow.

$$Y = Y_i - \frac{n\text{I}_2 F}{n\text{O}_2 \eta_p} N, \quad (2)$$

$N$  can be found from the energy conservation equation:

$$c_p [(n_p \eta_p + n_s \eta_s) T_0 - n_p \eta_p (T_{0i})_p - n_s \eta_s (T_{0i})_s] = q_\Delta n l_2 F N - q_{I_2} n l_2 F - q_{I^*} n l_2 F \frac{2K_e Y}{(K_e - 1)Y + 1}, \quad (3)$$

where  $c_p = 7/2 k$ ,  $T_0$  is the stagnation temperature of the flow in the reaction zone,  $(T_{0i})_p$  and  $(T_{0i})_s$  are the stagnation temperatures of the primary and secondary flows,  $q_\Delta = 11,340$  K,  $q_{I_2} = 18,400$  K and  $q_{I^*} = 10,954$  K

Find  $T_0$

$p$  is constant hence flow velocity  $V$  is constant ( $\rho V dV/dx = - dp/dx =$

$V^2/2 + c_p T = c_p T_0$ , hence  $\Delta(T_0/\mu) = \Delta(T/\mu)$ :

$$T_0 = T_{0c} \frac{\mu}{\mu_c} + T - T_c \frac{\mu}{\mu_c},$$

where  $T_c$  and  $T_{0c}$  are static and stagnation temperatures in the "cold" runs without iodine.

$T_c$  is found from  $T(nI_2)$  by extrapolation to to  $nI_2$ , corresponding to zero gain.

g and F are nonmonotonous functions of  $nI_2$ :

This was predicted in B. D. Barmashenko, A. Elior, E. Lebiush and ; Rosenwaks, J. Appl. Phys., **75**, 7653 (1994).

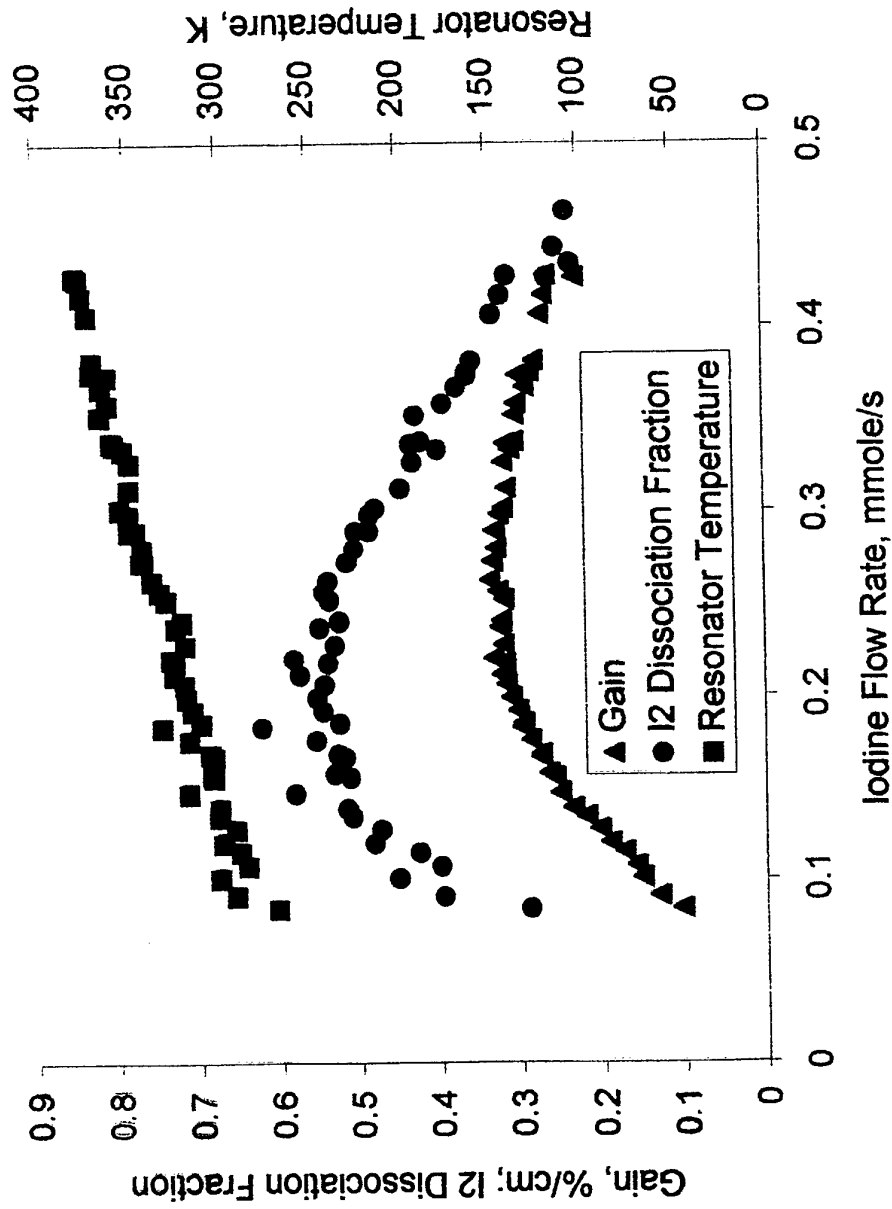
For low  $nI_2 < (nI_2)_c$ , F increases with  $nI_2$ . This is due to an increase of  $[I^*]$  that serve as the chain carriers for the dissociation reactions



For high  $nI_2 > (nI_2)_c$ , F decreases with increasing  $nI_2$ .  $O_2(^1\Delta)$ ,  $I^*$  and  $I_2$  are quenched by  $I_2$  which results in a retardation of the dissociation.



# Grid nozzle



Cl2 11.7 mmole

Yield 0.65

Utilization 0.92

Water 0.12

Sec. N2 1.36 mmole

Stag. Temp. 340

Cold Res. Temp. 260

Res. Press. 1.4 Torr

To find  $\eta_p$  and  $\eta_s$  we compared  $N(nI_2)$  with the theoretical value of  $N$

$$N_{th} = 1 + 1 / \eta_{dis} - \frac{(k_w nH_2O + k_o Y nO_2) \eta_p \ln(1 - F)}{\eta_{dis} k_7 nI_2} + \frac{2K_e Y}{(K_e - 1)Y + 1},$$

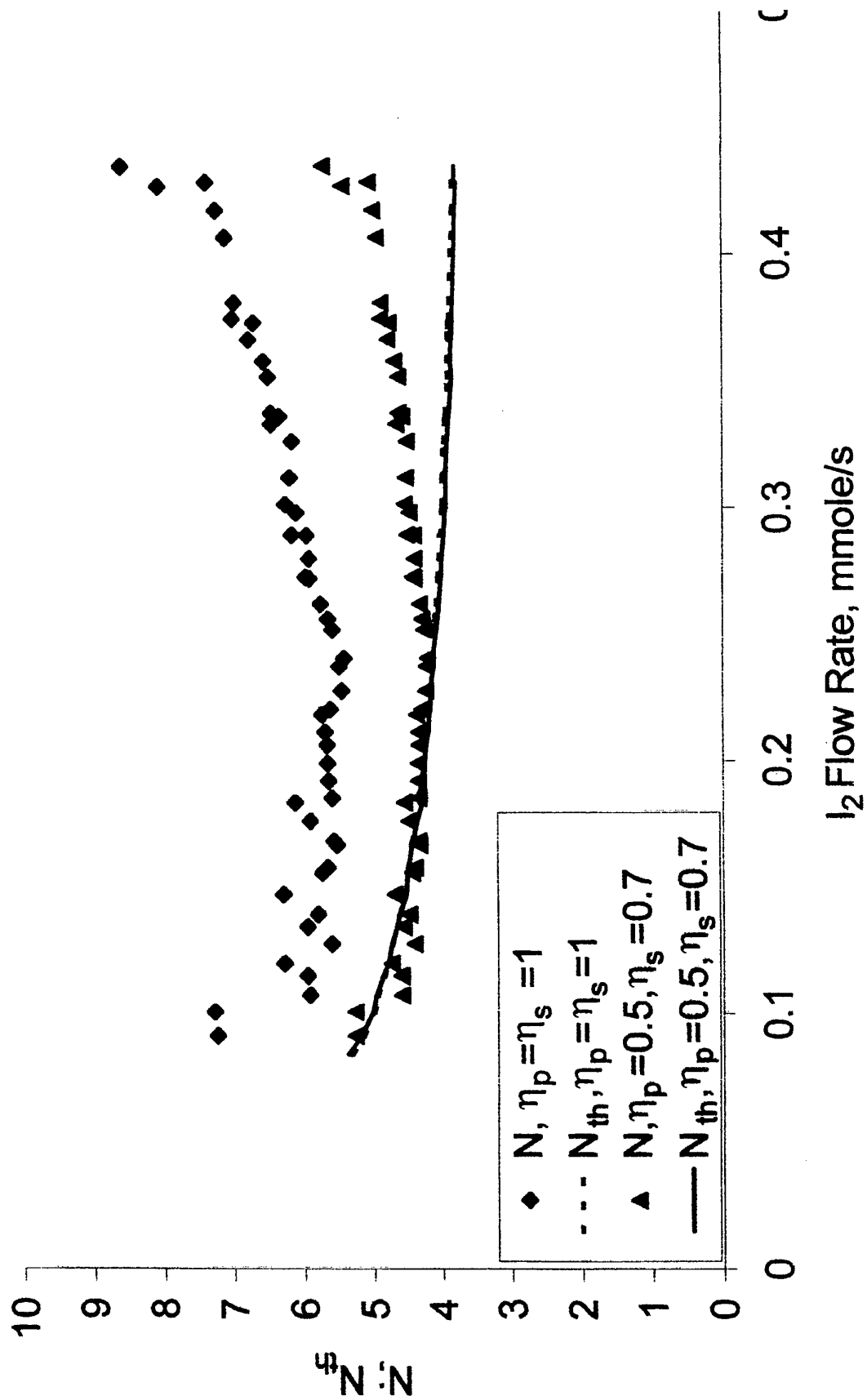
$\eta_{dis} = k_1[O_2(^1\Delta)] / (k_1[O_2(^1\Delta)] + \sum_M k_{qM}[M])$  is the dissociation

efficiency,  $k_1$  is the rate of reaction  $O_2(^1\Delta) + I_2^* \rightarrow O_2(^3\Sigma) + 2I$

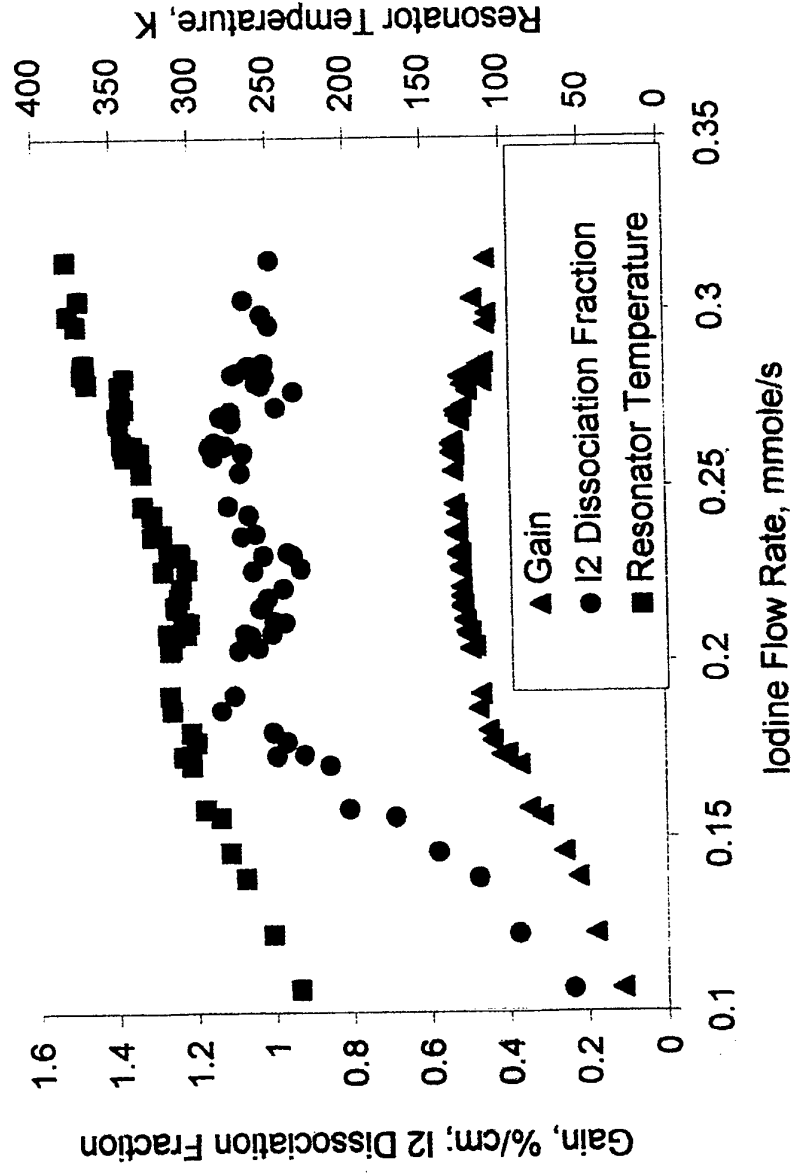
B. D. Barmashenko and S. Rosenwaks, AIAA Journal, **34**, 2569 (1996)

V. Quan, Proc. SPIE, **2989**, 114 (1997).

# Grid nozzle

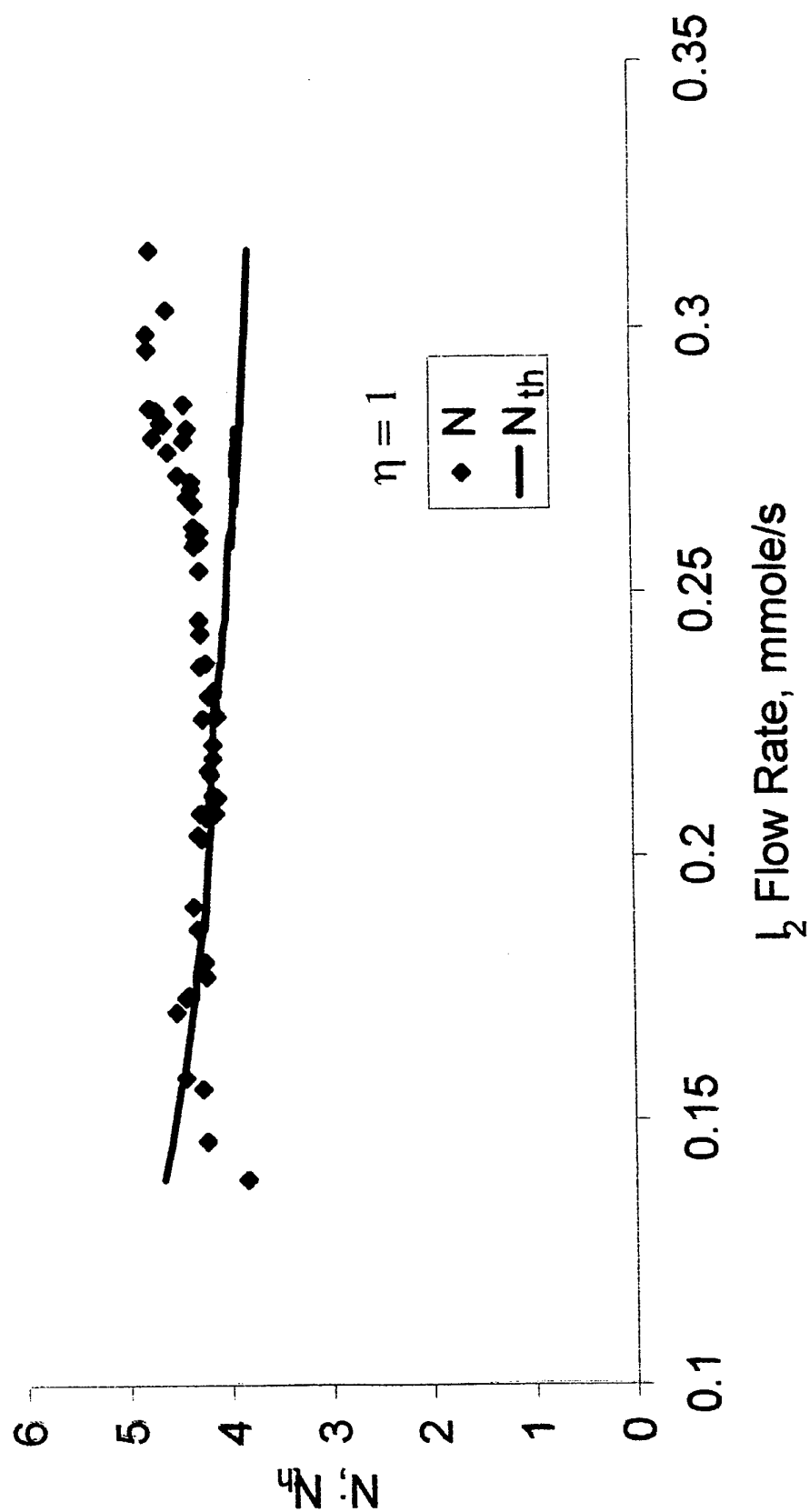


# Slit nozzle #1

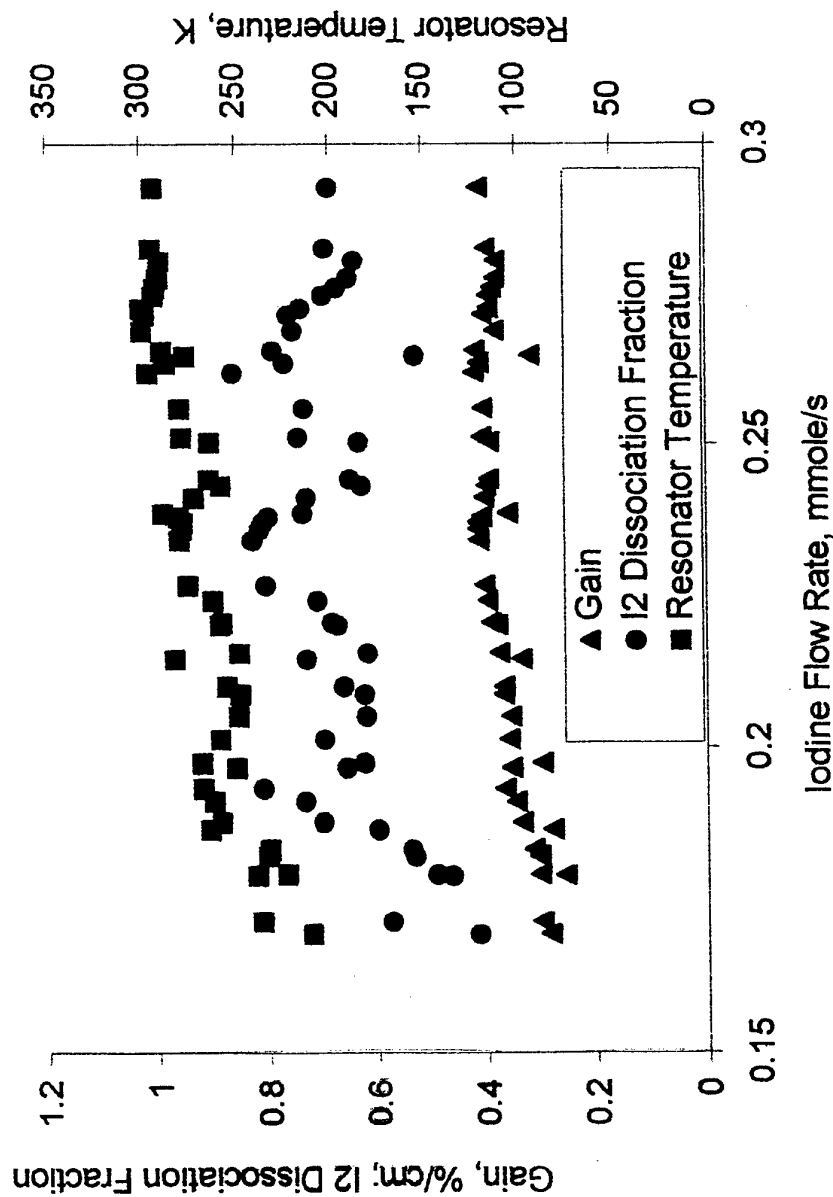


Cl<sub>2</sub> 11.7 mmole  
 Yield 0.6  
 Utilization 0.9  
 Water 0.12  
 Sec. N<sub>2</sub> 2.5 mmole/  
 Stag. Temp. 320  
 Cold Res. Temp. 260  
 Res. Press. 1.4 Torr

# Slit nozzle #1



# Slit nozzle #1 (high Cl2 flow rate)



Cl2 19.5 mmole

Yield 0.55

Utilization 0.9

Water 0.12

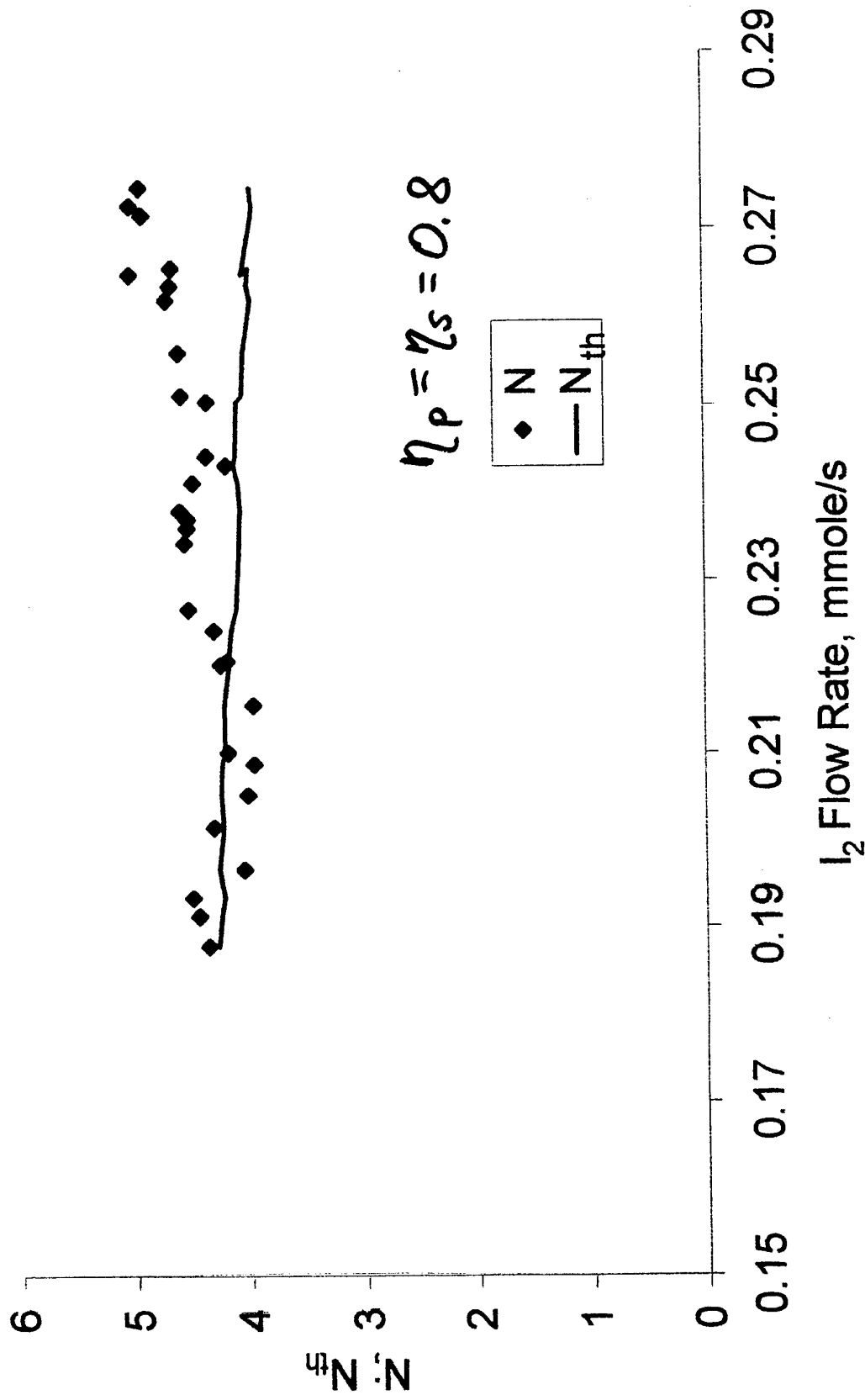
Sec. N2 2.5 mmole/l

Stag. Temp. 320

Cold Res. Temp. 230

Res. Press. 1.55 Torr

Slit nozzle No. 1 (high  $\text{Cl}_2$  flow rate)



# Slit nozzle #2

Cl2 11.8 mmole/s

Yield 0.55

Utilization 0.9

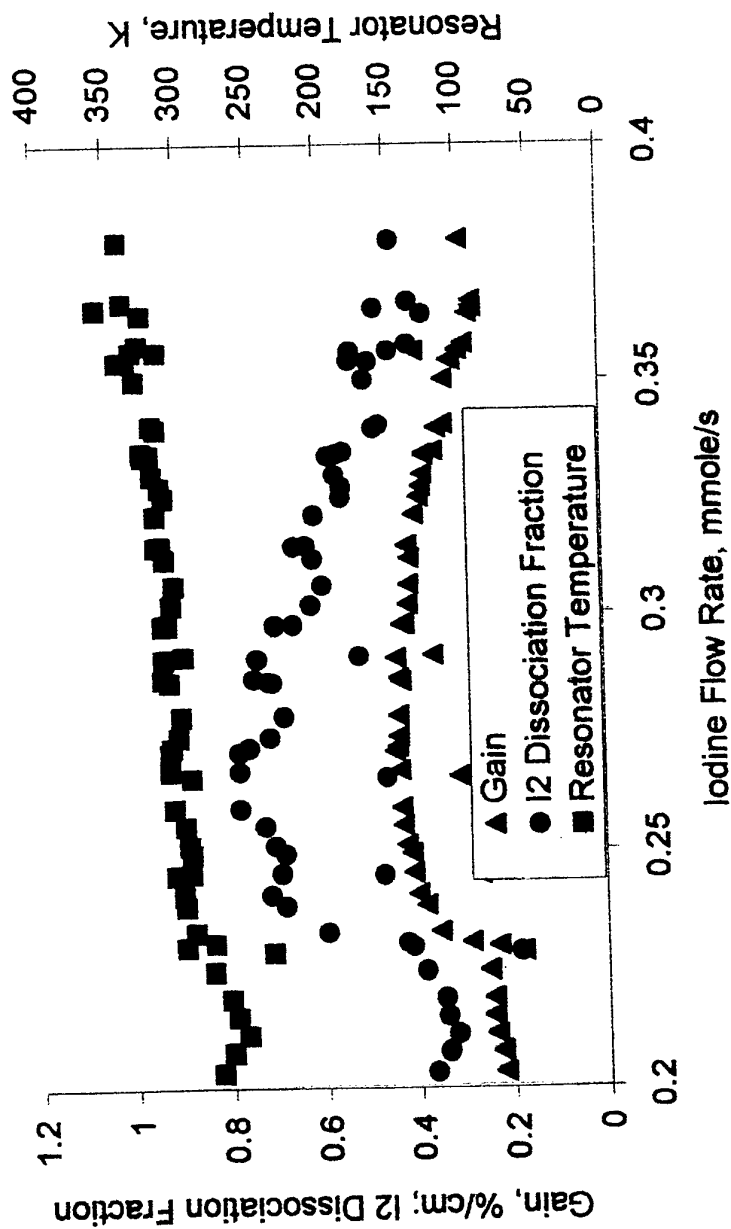
Water 0.12

Sec. N2 4 mmole/s

Stag. Temp. 350

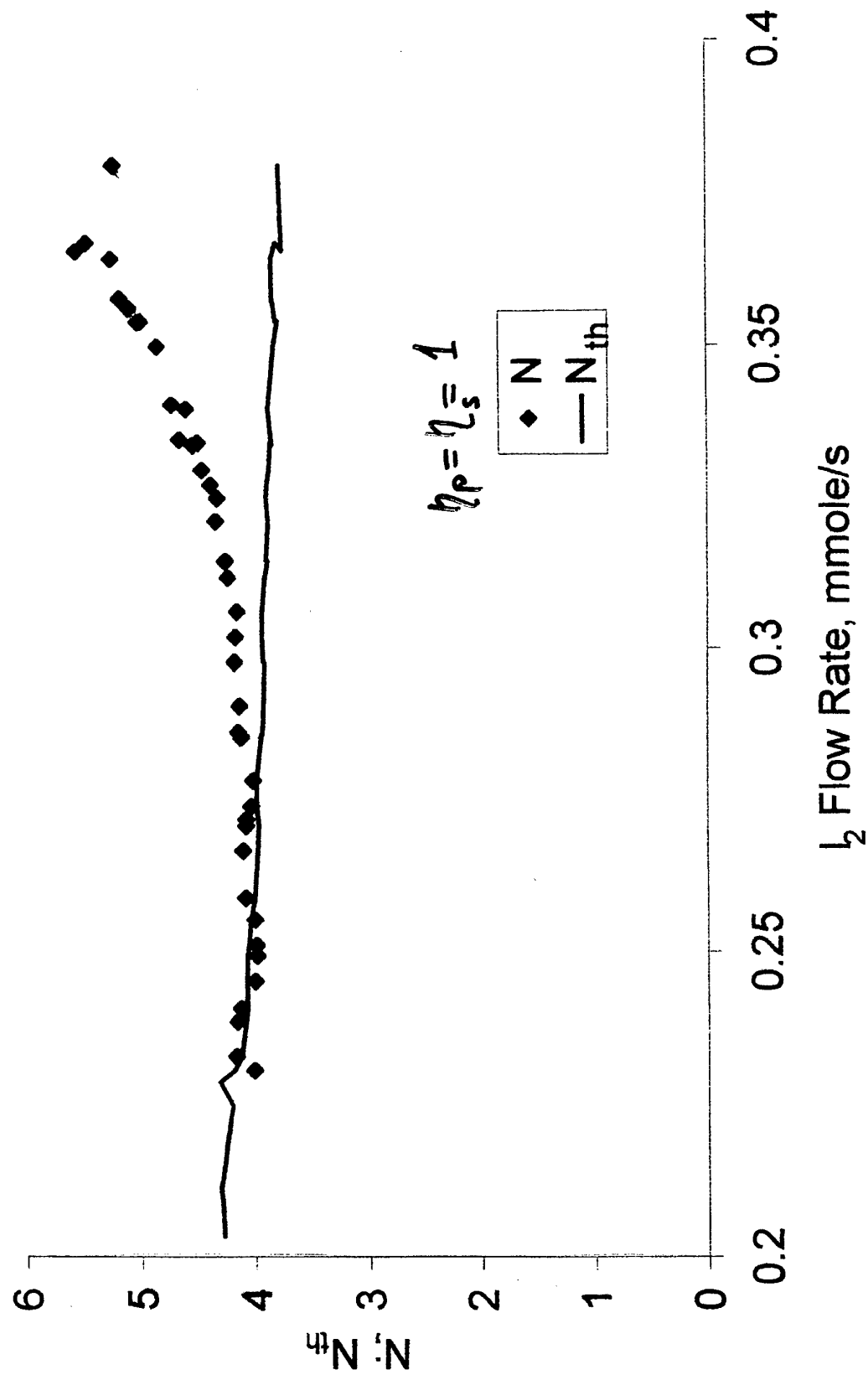
Cold Res. Temp. 260

Res. Press. 1.45 Torr

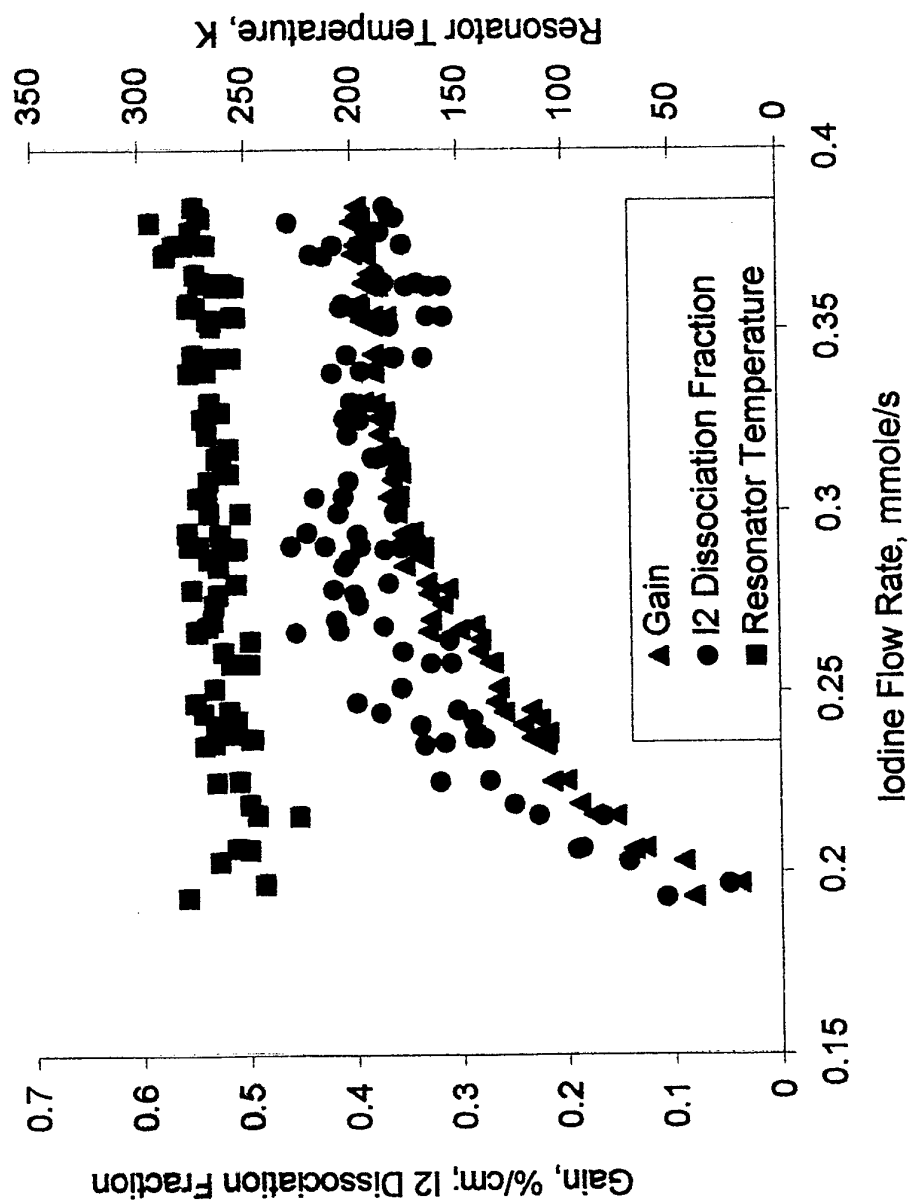




# Slit nozzle No.2



# Slit nozzle #3 (supersonic injection)



Cl<sub>2</sub> 11.7 mmol

Yield 0.55

Utilization 0.9

Water 0.12

Sec. N<sub>2</sub> 7 mmole/s

Stag. Temp. 320

Cold Res. Temp. 260

Res. Press. 1.55 Torr

Grid nozzle:  $F = 0.55$  can be explained by slow mixing rate.

Both  $\eta_s$  and  $\eta_p$  are small.

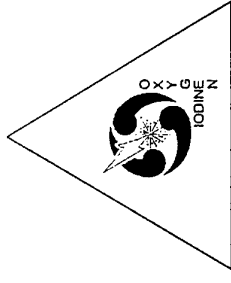
Slit nozzle No. 1: for low Cl2 (11.7 mmole/s)  $F = 1$ , is much higher than for the grid nozzle due to higher mixing efficiency caused by large optimal penetration. For higher Cl2 (19.5 mmole/s)  $F$  is about 0.8; smaller  $F$  is due to smaller mixing efficiency and higher flow velocity.

Slit nozzle No. 2:  $F$  is  $\sim 0.8$ , i. e. smaller than for the nozzle No.1.

Slit nozzle No. 3 (supersonic injection):  $F$  is  $\sim 0.45$ , i. e. much smaller than for the nozzle No.1.

## Conclusions

1. An analytical method is developed, which enables the use of dependencies of  $g$  and  $T$  in the resonator of the supersonic CO<sub>2</sub> laser, for calculation of  $F$  and  $N$ .
2.  $F$  is a nonmonotonous function of  $n\text{I}_2$ .
3. Maximum values of  $F$  are found for different types of the nozzle. The highest  $F \sim 1$  is achieved for slit nozzle No. 1 with transonic injection of iodine and small Cl<sub>2</sub> flow rate of 11.7 mmole/s.
4. For the grid nozzle the mixing efficiencies are small ( $\sim 0.5 - 0.7$ ). For the slit nozzle No.1 the mixing efficiency is much higher than for the grid nozzle ( $\sim 1$ ). For higher Cl<sub>2</sub> flow rate mixing efficiency smaller ( $\sim 0.8$ ).



# An Investigation of Supersonic Mixing Mechanisms for the Chemical Oxygen- Iodine Laser (COIL)

Dr. Timothy Madden and Dr. Gordon Hager

*Air Force Research Laboratory*

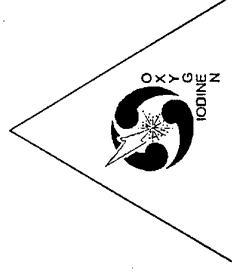
Alan Lampson and Dr. Peter Crowell

*Northrup Logicon Division*



# Outline

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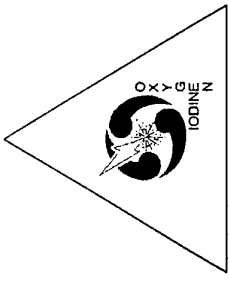


- Introduction
- Methodology
- Results
- Summary and Conclusion



# Introduction

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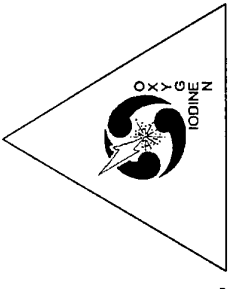


- Traditional COLL's have injected the  $I_2$ /diluent mixture in the subsonic region of the mixing nozzle.
  - This placement was driven by the interplay between mixing,  $I_2$  dissociation, and transport through the nozzle flow.
- Can the  $I_2$ /diluent mixture be injected in the supersonic region of the nozzle without degrading performance?



## Introduction (cont.)

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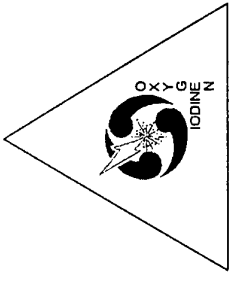
- Supersonic injection offers potential performance improvements.
  - De-couples the generator from the injection process.
  - Improved mirror loadings.
  - Lower deactivation losses.
    - Introduces the possibility of injecting I atoms with minimal I\* deactivation.
    - Supersonic injection is logical for I atoms because it minimizes I\* deactivation losses during transport.





# Methodology

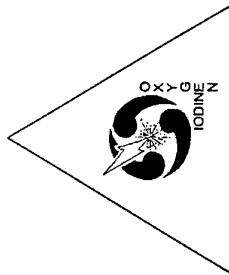
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- The different injection concepts are modeled using the MINT CFD code from Scientific Research Associates.
  - Solves the 3D Navier-Stokes equations coupled to finite-rate chemistry, detailed molecular diffusion, and Fabry-Perot power extraction models.
  - Extensively validated as an accurate tool for modeling COIL flowfields.



# Methodology (cont.)

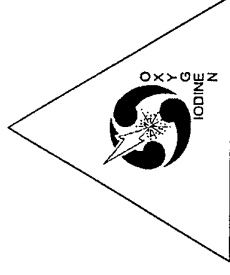


## AFRL Standard COIL Chemistry Mechanism

	Reaction	Rate (cc/molecule-sec)
1	$O_2(^1\Delta) + O_2(^1\Delta) \rightarrow O_2(^1\Sigma) + O_2(^3\Sigma)$	$2.7 \cdot 10^{-17}$
2	$O_2(^1\Sigma) + H_2O \rightarrow O_2(^3\Sigma) + H_2O$	$6.7 \cdot 10^{-12}$
3	$O_2(^1\Delta) + O_2(^3\Sigma) \rightarrow O_2(^3\Sigma) + O_2(^3\Sigma)$	$1.6 \cdot 10^{-18}$
4	$O_2(^1\Delta) + H_2O \rightarrow O_2(^3\Sigma) + H_2O$	$4.0 \cdot 10^{-18}$
5	$O_2(^1\Delta) + Cl_2 \rightarrow O_2(^3\Sigma) + Cl_2$	$6.0 \cdot 10^{-18}$
6	$O_2(^1\Delta) + He \rightarrow O_2(^3\Sigma) + He$	$8.0 \cdot 10^{-21}$
7	$I_2 + O_2(^1\Sigma) \rightarrow 2I(^2P_{3/2}) + O_2(^3\Sigma)$	$4.0 \cdot 10^{-12}$
8	$I_2 + O_2(^1\Sigma) \rightarrow I_2 + O_2(^1\Delta)$	$1.6 \cdot 10^{-11}$
9	$I_2 + O_2(^1\Delta) \rightarrow I_2 + O_2(^3\Sigma)^*$	$7.0 \cdot 10^{-15}$
10	$I_2 + I(^2P_{1/2}) \rightarrow I(^2P_{3/2}) + I_2$	$3.8 \cdot 10^{-11}$
11	$I_2^* + O_2(^1\Delta) \rightarrow 2I(^2P_{3/2}) + O_2(^3\Sigma)$	$3.0 \cdot 10^{-10}$
12	$I_2^* + O_2(^3\Sigma) \rightarrow I_2 + O_2(^3\Sigma)$	$5.0 \cdot 10^{-11}$
13	$I_2^* + H_2O \rightarrow I_2 + H_2O$	$3.0 \cdot 10^{-10}$
14	$I_2^* + He \rightarrow I_2 + He$	$3.2 \cdot 10^{-11}$
15	$I(^2P_{3/2}) + O_2(^1\Delta) \rightarrow I(^2P_{1/2}) + O_2(^3\Sigma)$	$2.33 \cdot 10^{-8}/T$
16	$I(^2P_{1/2}) + O_2(^3\Sigma) \rightarrow I(^2P_{3/2}) + O_2(^1\Delta)$	$3.1 \cdot 10^{-8}/T$
17	$I(^2P_{3/2}) + O_2(^1\Delta) \rightarrow I(^2P_{3/2}) + O_2(^3\Sigma)$	$\cdot \exp(-401.4/T)$
18	$I(^2P_{1/2}) + O_2(^1\Delta) \rightarrow I(^2P_{3/2}) + O_2(^1\Sigma)$	$1.0 \cdot 10^{-15}$
19	$I(^2P_{1/2}) + O_2(^1\Delta) \rightarrow I(^2P_{3/2}) + O_2(^3\Sigma)$	$1.1 \cdot 10^{-13}$
20	$I(^2P_{1/2}) + I(^2P_{3/2}) \rightarrow I(^2P_{3/2}) + I(^2P_{3/2})$	$5.0 \cdot 10^{-14}$
21	$I(^2P_{1/2}) + H_2O \rightarrow I(^2P_{3/2}) + H_2O$	$1.6 \cdot 10^{-14}$
		$2.0 \cdot 10^{-12}$



## Methodology (cont.)

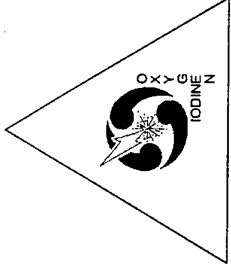


- One subsonic and two supersonic injection concepts are modeled:
  - Subsonic and supersonic I<sub>2</sub>/He injection.
  - I/DF/He injection
    - I atoms are assumed to be the product of the reaction  
$$\text{F} + \text{DI} \rightarrow \text{DF} + \text{I}.$$

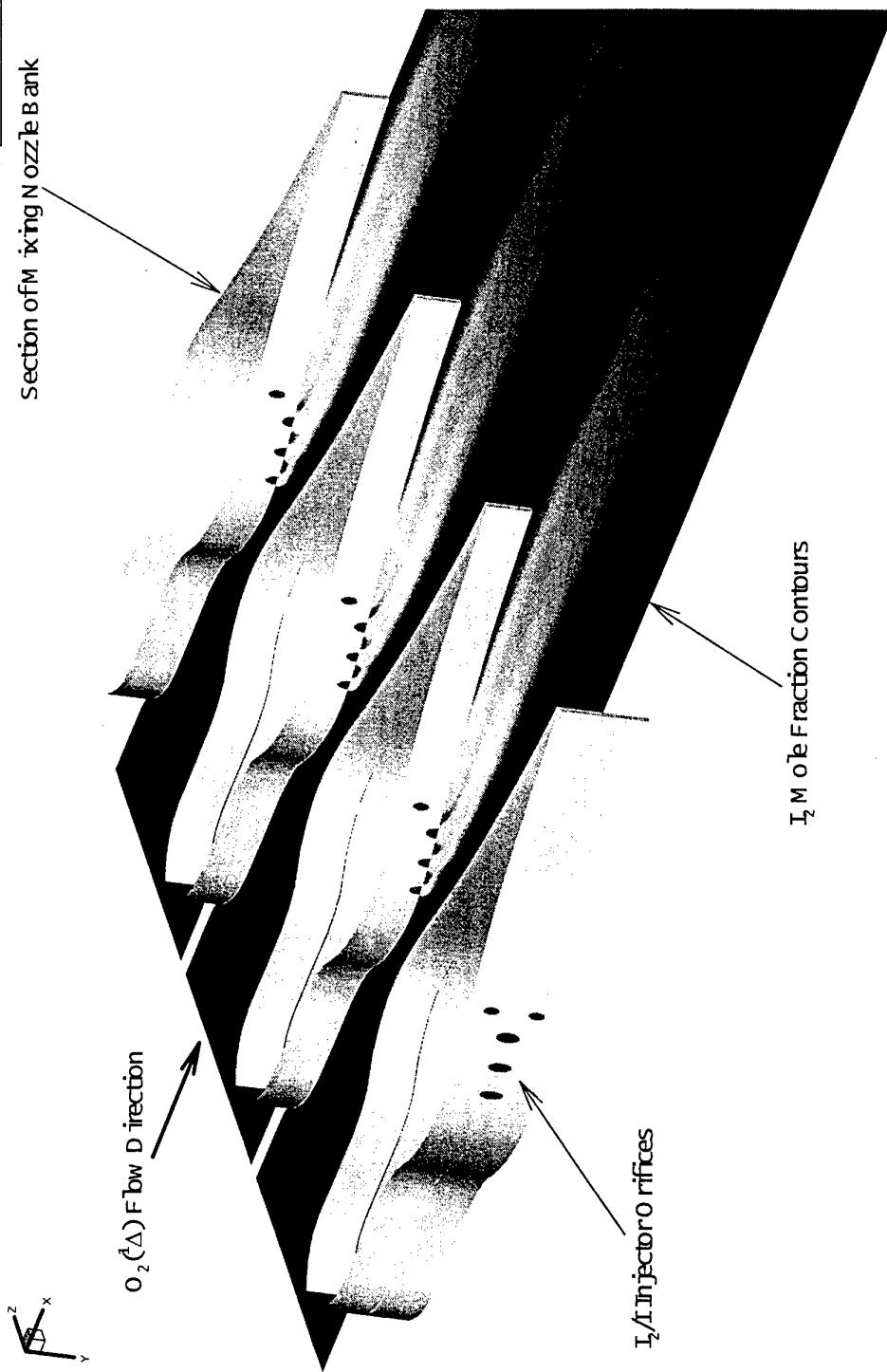
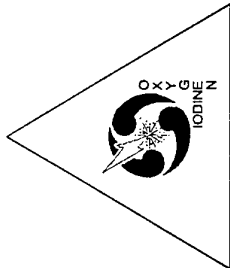


## Methodology (cont.)

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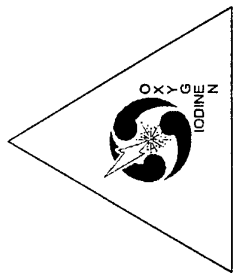
- Flow conditions
  - $\text{He}/\text{Cl}_2 = 4/1$
  - $\text{I}_2/\text{O}_2 = 0.018$ ,  $\text{I}/\text{O}_2 = 0.036$
  - Yield nominally  $> 50\%$
  - Low  $\text{H}_2\text{O}$  - condensation assumed negligible.



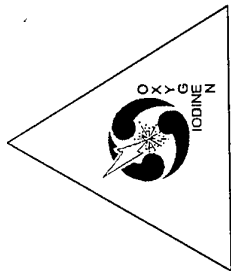
3D MINT CFD Simulation of Supersonic Injection of  $I_2$  into  $O_2$  (Δ) Flow



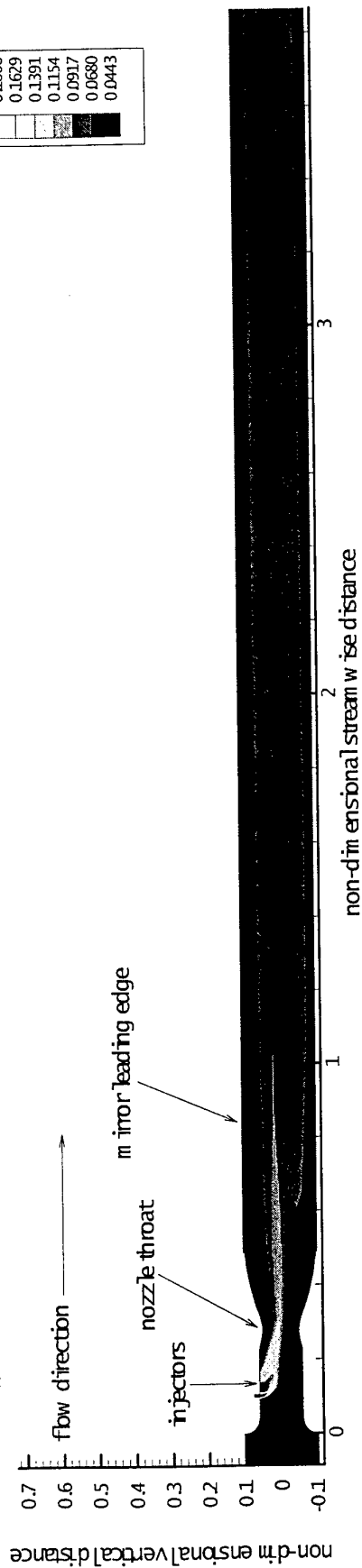
## Results



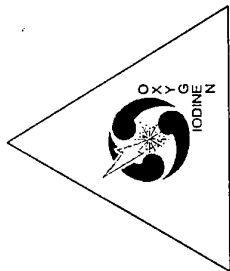
- Subsonic  $I_2/He$  injection.



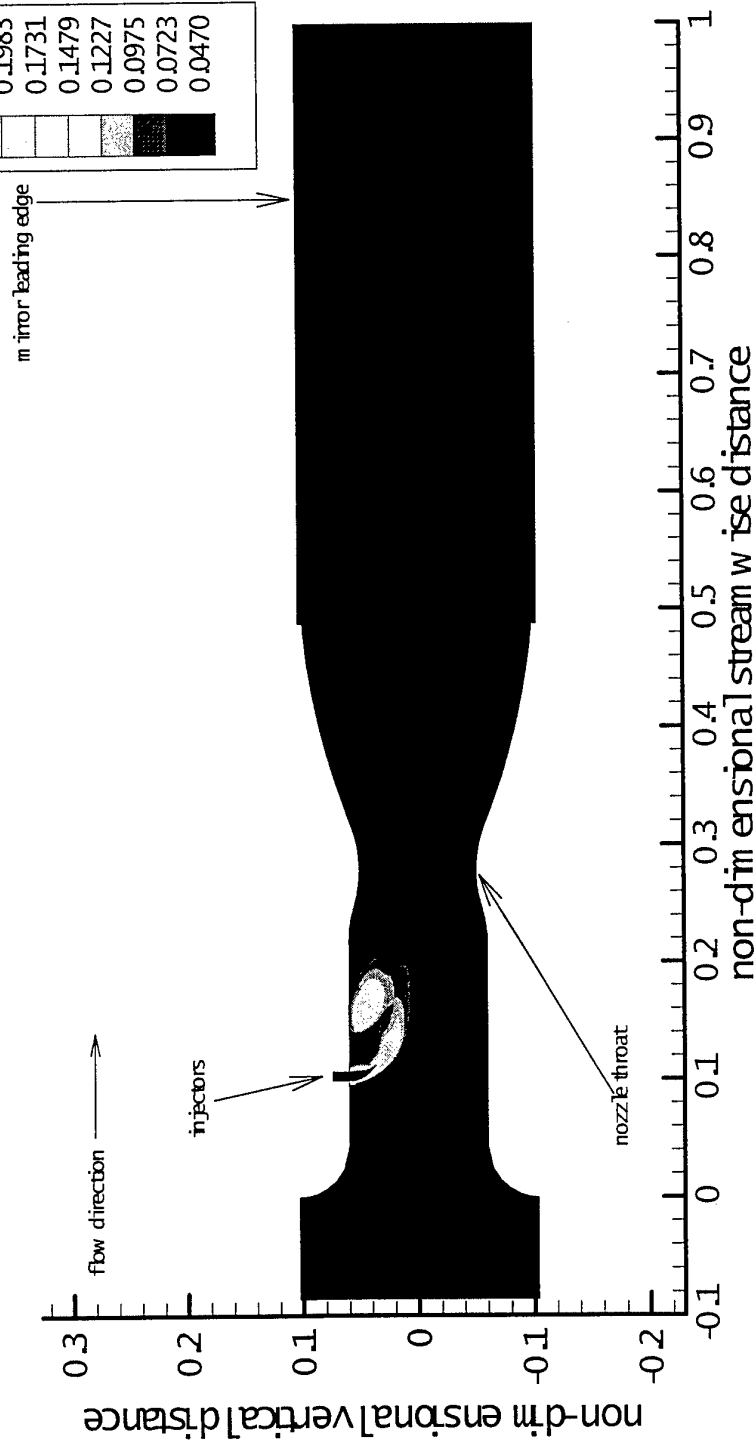
# Total Iodine Mass Fraction from MINT Simulation of COIL Mixing Nozzle with Subsonic Injection, $I_2$ Injected



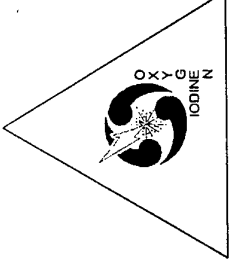
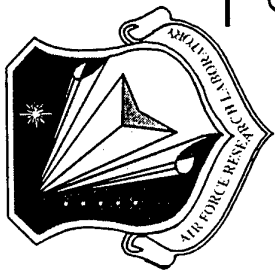
0.4000
0.3763
0.3526
0.3289
0.3051
0.2814
0.2577
0.2340
0.2103
0.1866
0.1629
0.1391
0.1154
0.0917
0.0680
0.0443



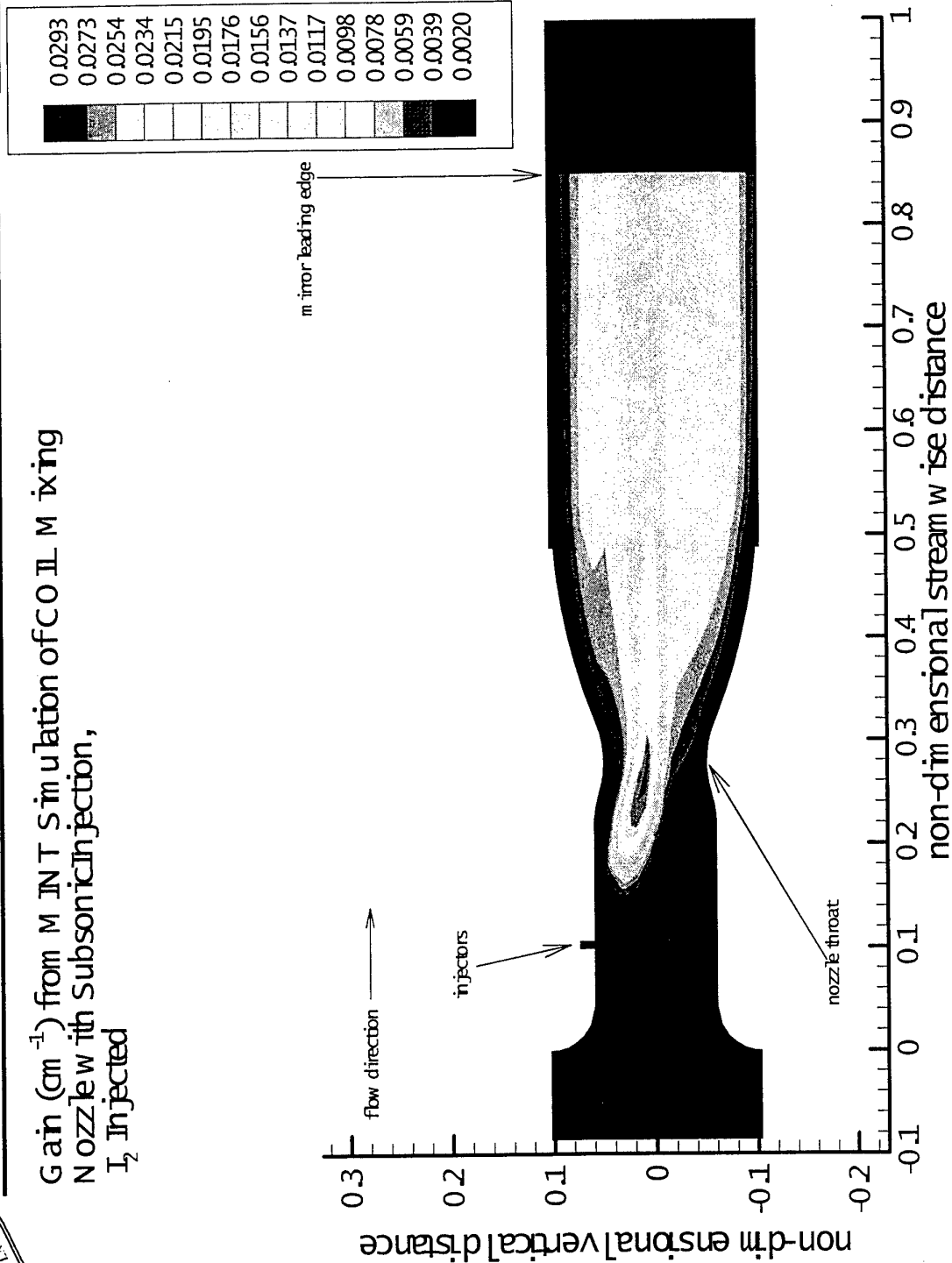
# $I_2$ Mass Fractions from MINT Simulation of COIL Mixing Nozzle with Subsonic Injection, $I_2$ Injected





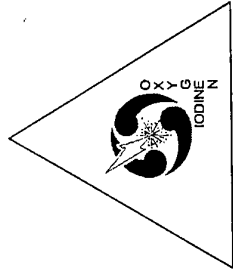


# Gain ( $\text{cm}^{-1}$ ) from MINT Simulation of COIL Mixing Nozzle with Subsonic Injection, $\text{I}_2$ Injected

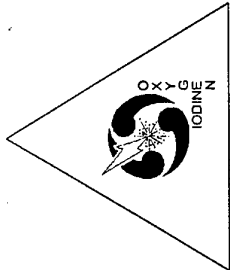




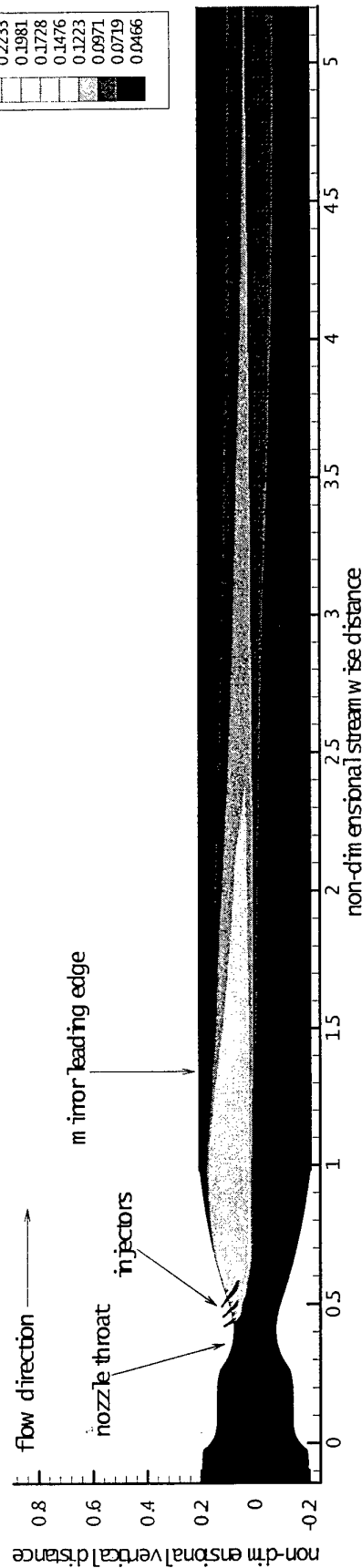
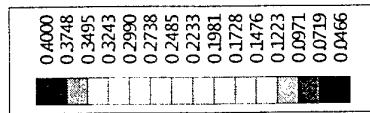
## Results

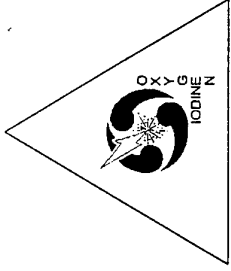
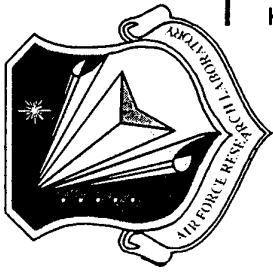


- Supersonic  $I_2/He$  injection.

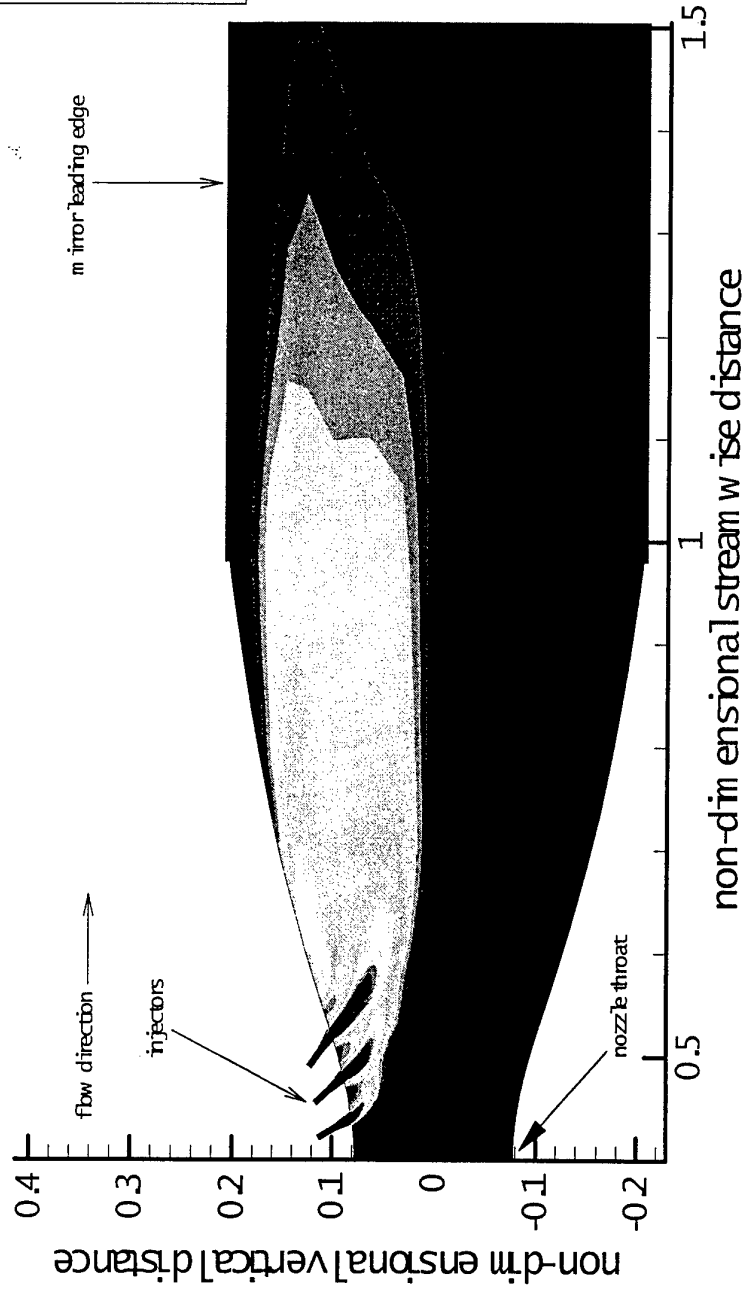
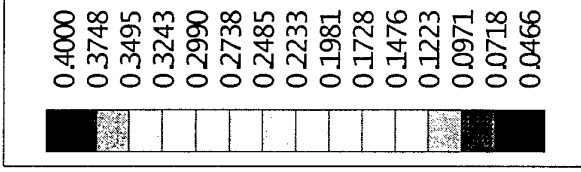


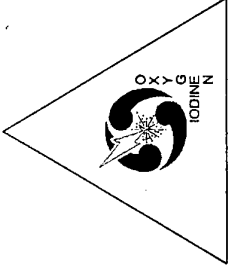
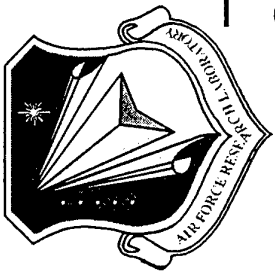
# Total Iodine Mass Fraction from MINT Simulation of COIL Mixing Nozzle with Supersonic Injection, $I_2$ Injected



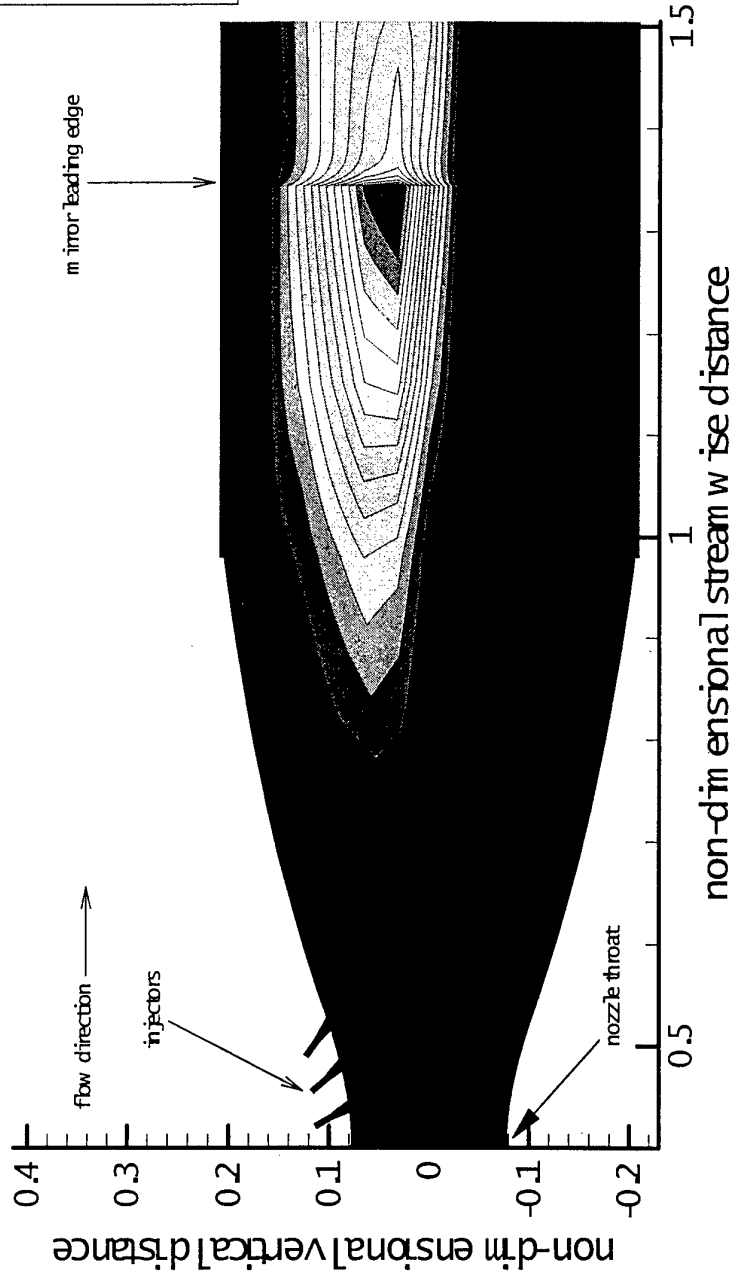


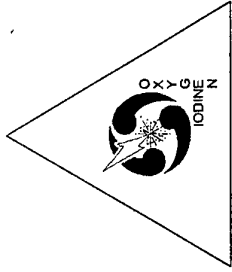
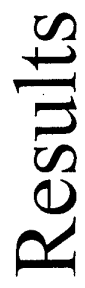
# $I_2$ Mass Fractions from MINT Simulation of COIL Mixing Nozzle with Supersonic Injection, $I_2$ Injected



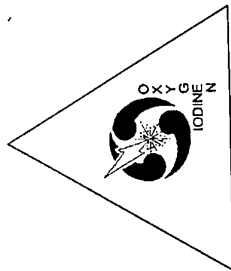


Gain ( $\text{cm}^{-1}$ ) from MINT simulation of COIL Mixing  
Nozzle with Supersonic Injection,  
 $\text{I}_2$  Injected

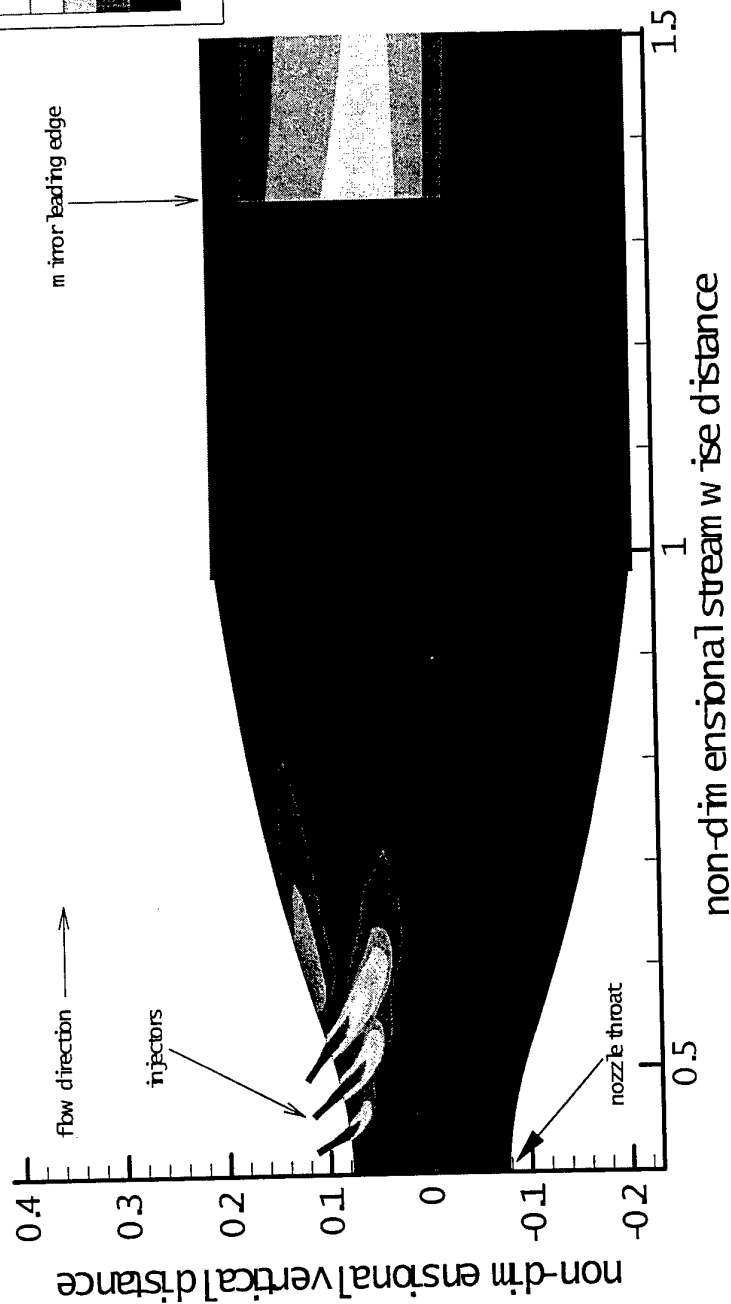


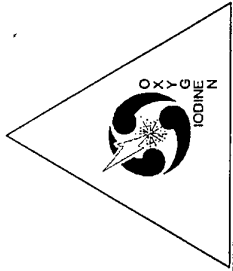


- I/DF/He injection

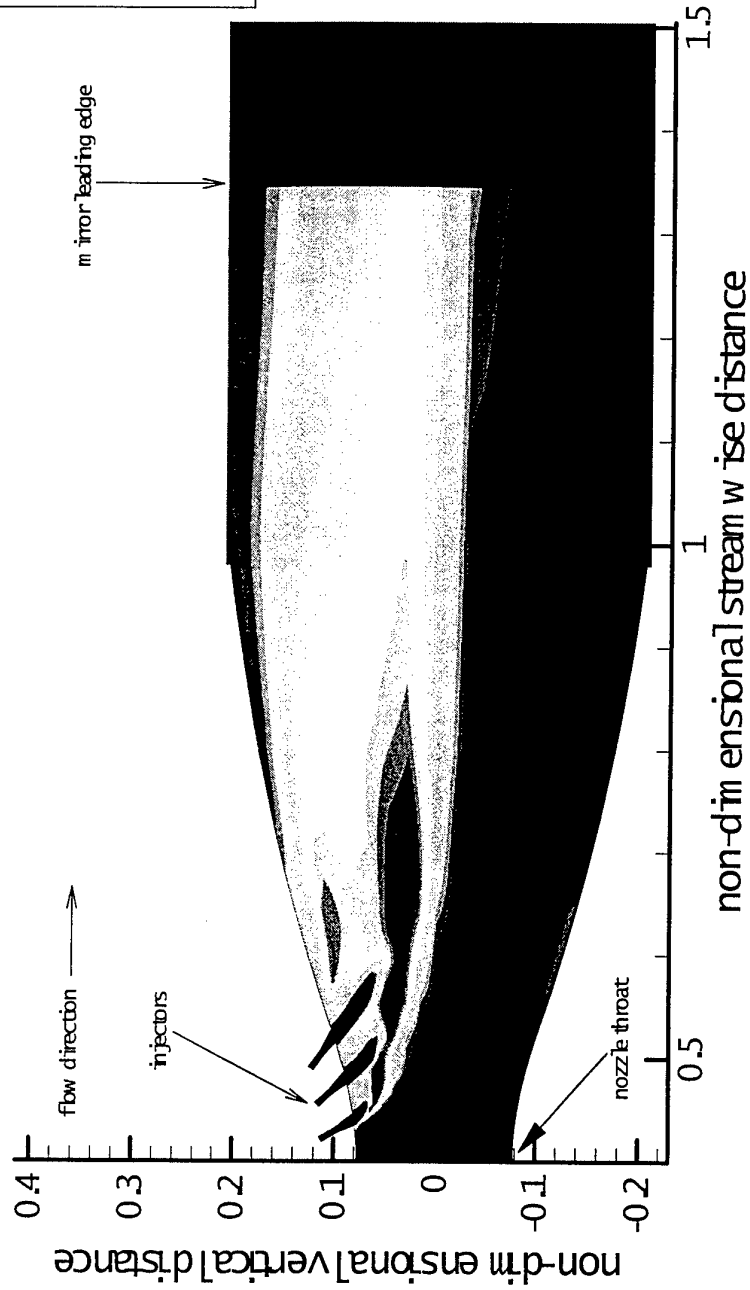


# Mass Fraction from MINT Simulation of COIL Mixing Nozzle with Supersonic Injection, Ions Injected





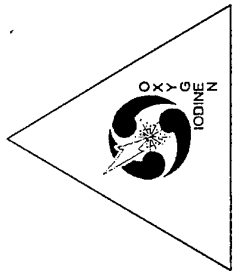
Gain ( $\text{cm}^{-1}$ ) from MINT simulation of COIL Mixing  
Nozzle with Supersonic Injection,  
I atoms injected



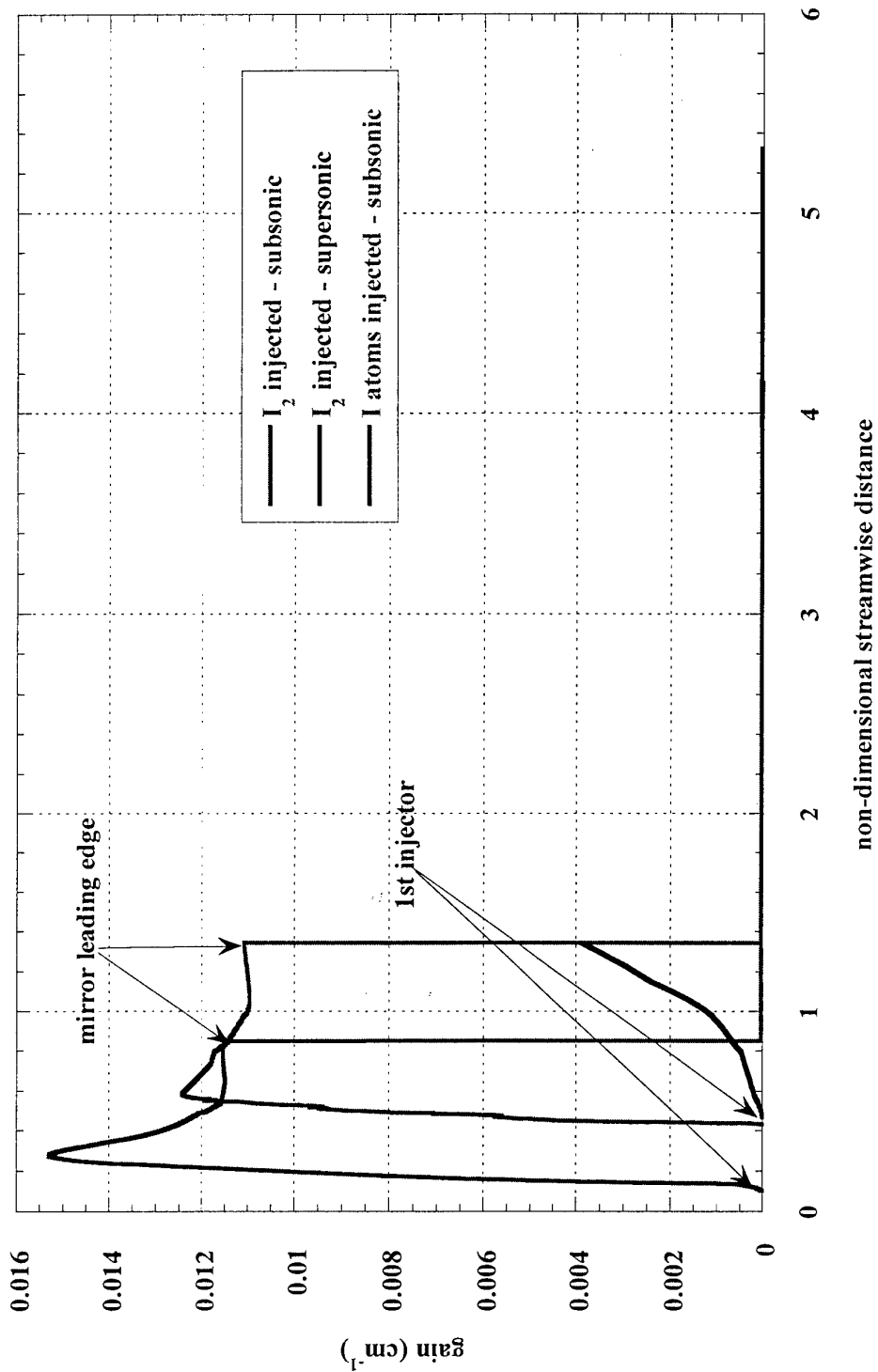
0.0375  
0.0348  
0.0322  
0.0295  
0.0268  
0.0241  
0.0214  
0.0188  
0.0161  
0.0134  
0.0107  
0.0080  
0.0054  
0.0027  
0.0000

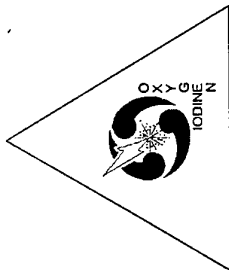






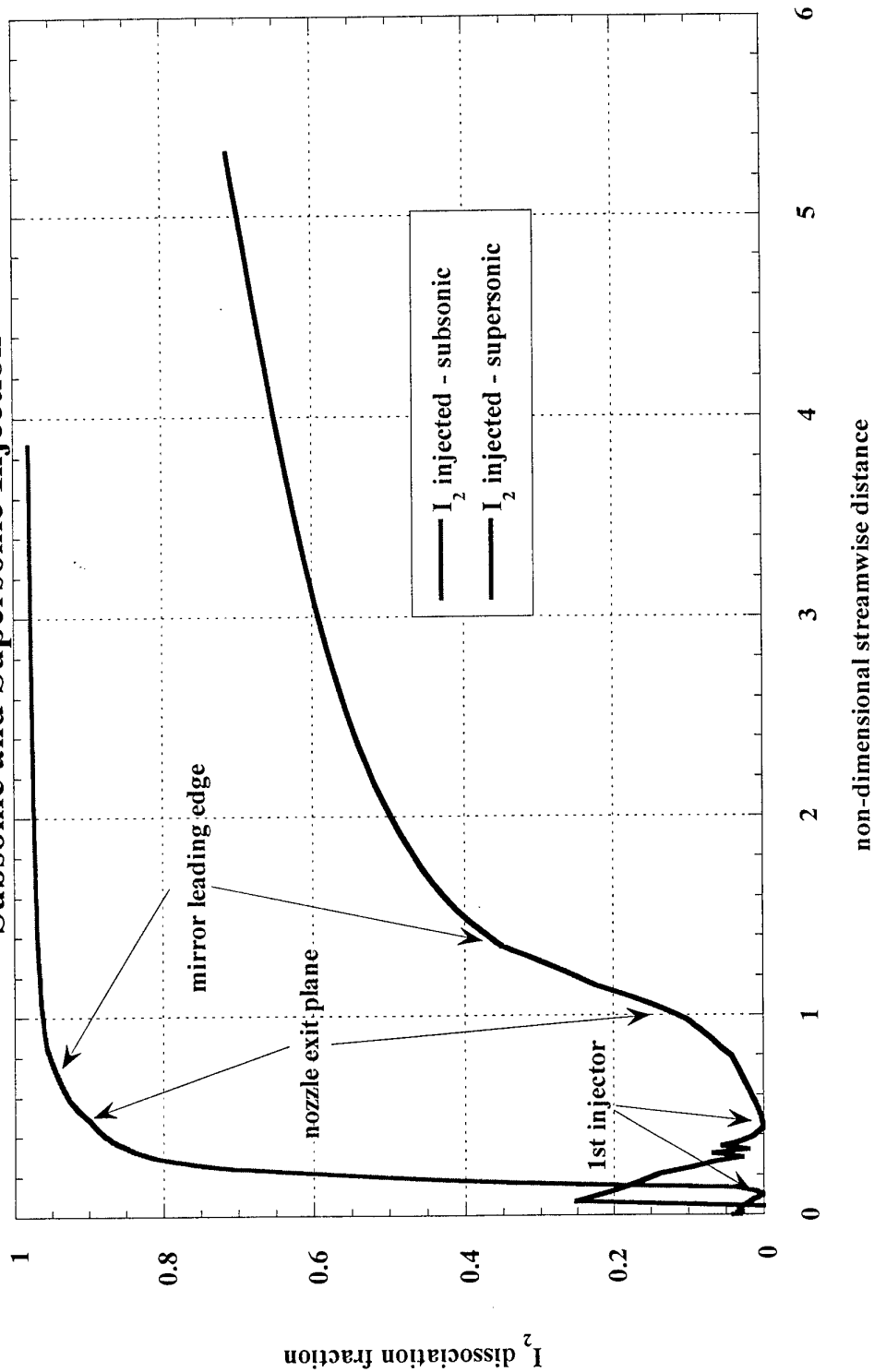
## Comparison of MINT Model Predictions of Average Gain using Subsonic and Supersonic Injection

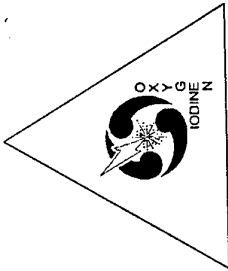




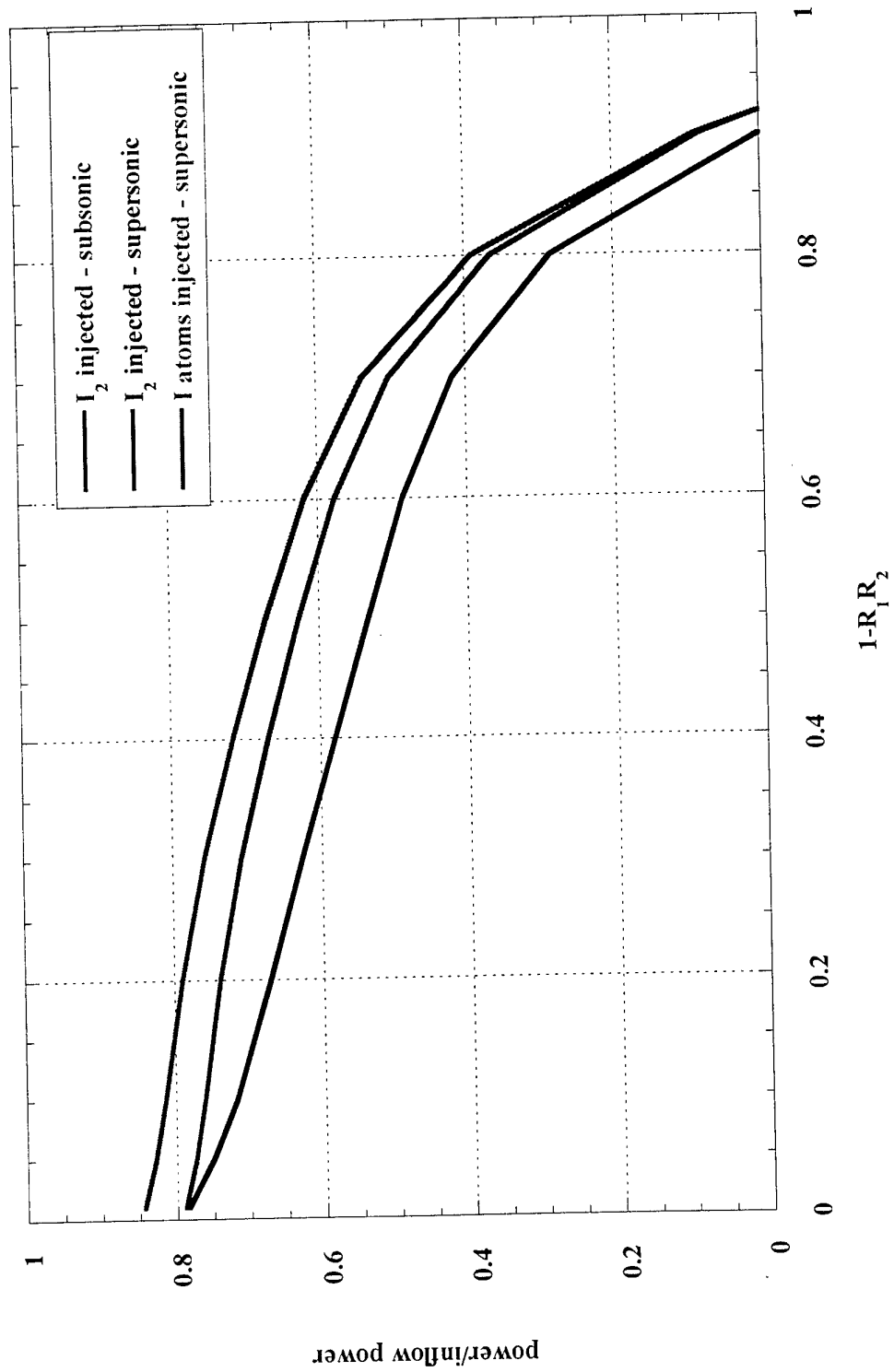
## Comparison of MINT Model Predictions of $I_2$ Dissociation using

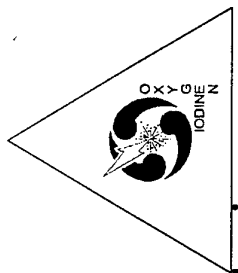
### Subsonic and Supersonic Injection





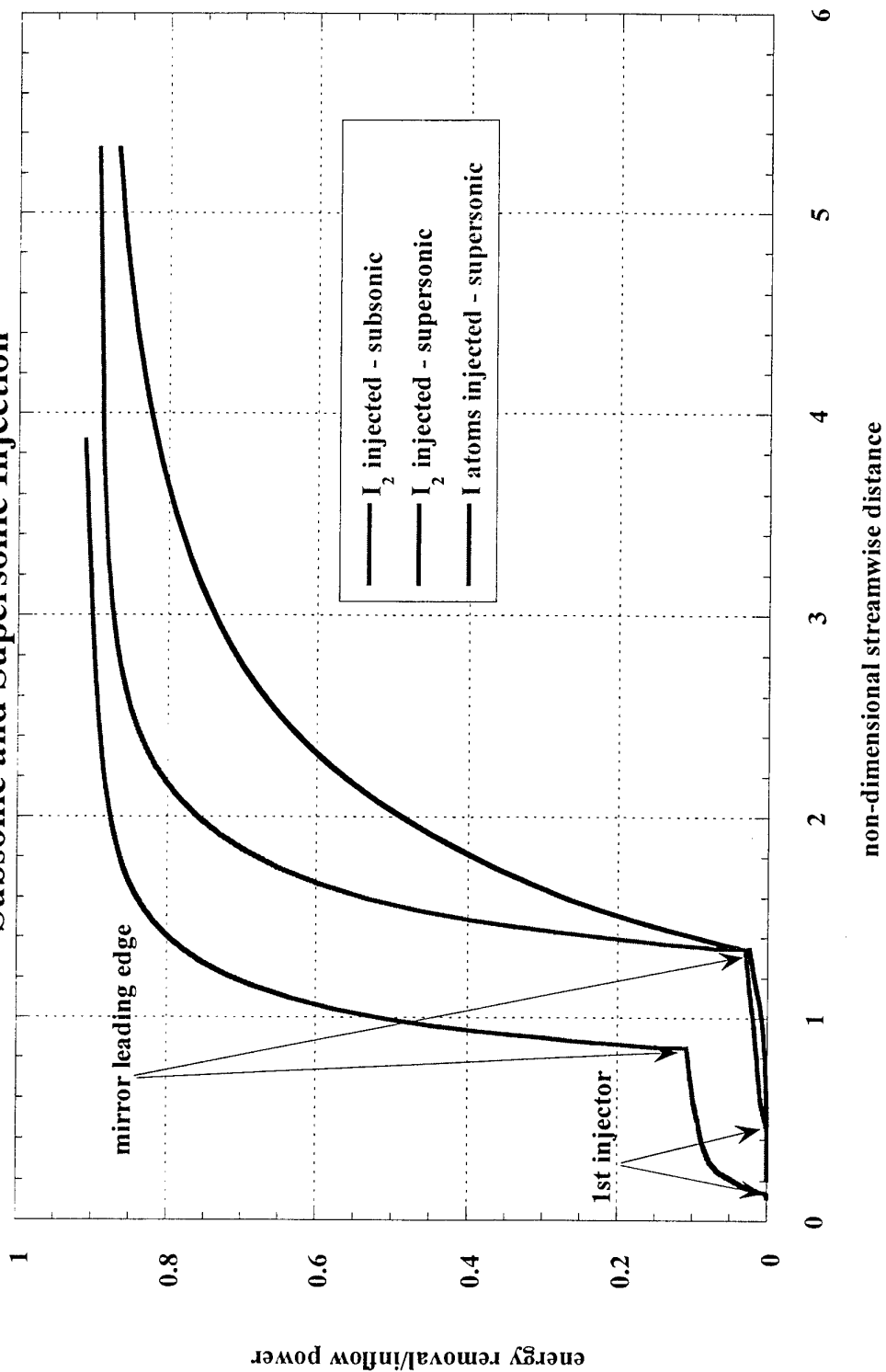
## Comparison of MINT Model Predictions of Power Extraction using Subsonic and Supersonic Injection

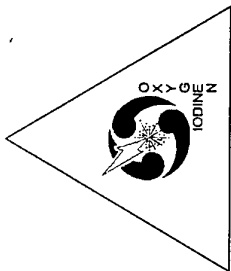




# Comparison of MINT Model Predictions of $O_2(^1\Delta)$ Energy Removal using

## Subsonic and Supersonic Injection



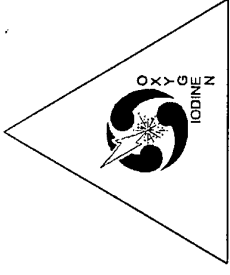


Quantity/Inflow Power	Subsonic I <sub>2</sub> Injection	Supersonic I <sub>2</sub> Injection	Supersonic I Atom Injection
Power Extracted	78.8%	78.3%	84.3%
Power in Flow at Cavity Exit	8.9%	13.2%	10.6%
available	2.6%	4.9%	2.2%
unavailable	6.3%	8.3%	8.4%
Lost Upstream of Resonator	10.9%	2.6%	3.1%
Losses in the Resonator	1.4%	6.0%	2.0%
Losses before Cavity Exit	12.3%	8.5%	5.1%
<b>Total Losses</b>	21.2%	21.7%	15.7%
<b>Cavity Temperature (K)</b>	151	169	170
<b>Cavity Mach Number</b>	2.25	1.91	1.99



## Summary and Conclusions

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- $I_2$  supersonic injection shows potential as an alternative to subsonic injection.
  - 0% outcoupling power equals subsonic power despite incomplete dissociation.
- I atom supersonic injection allows more power to be extracted than the  $I_2$  injection schemes over all of the outcoupling range.
  - No  $I_2$  dissociation cost.

**COIL-R&D WORKSHOP, *Prague*' 99**

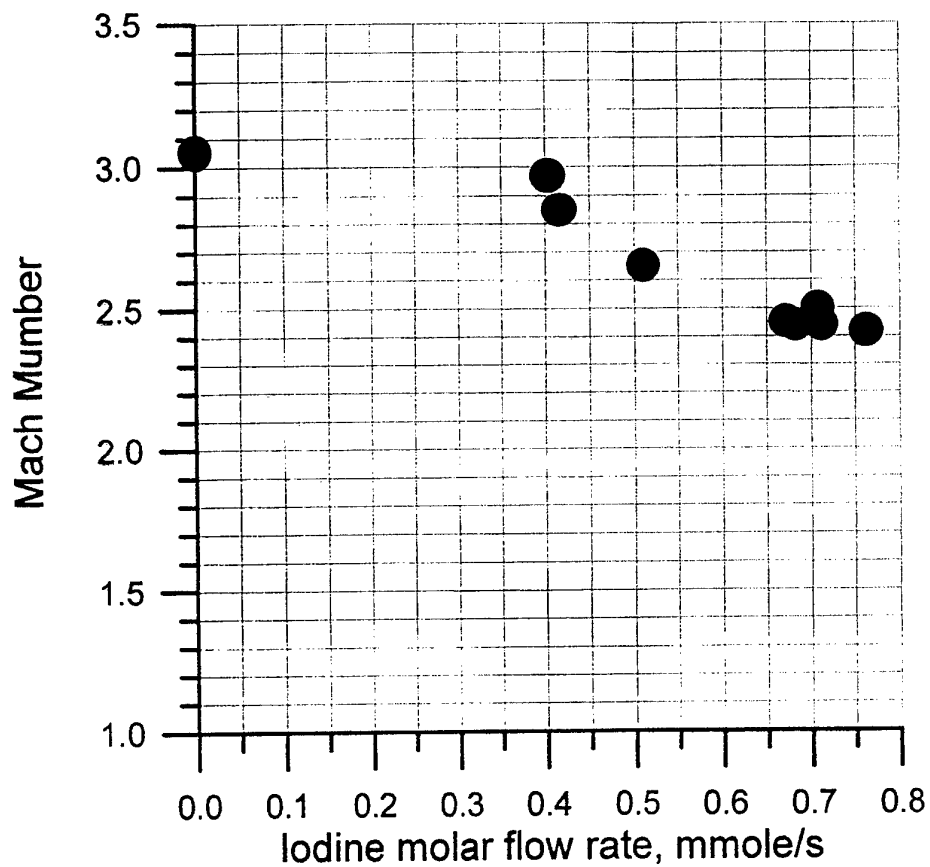
Lebedev Physical Institute, Samara Branch

Nikolaev V.D., Zagidullin M.V.

*The gas dynamic parameters, efficiency of mixing and  
lasing in COIL with ejector array of supersonic nozzles*

### Dependence of Mach number on iodine molar flow rate

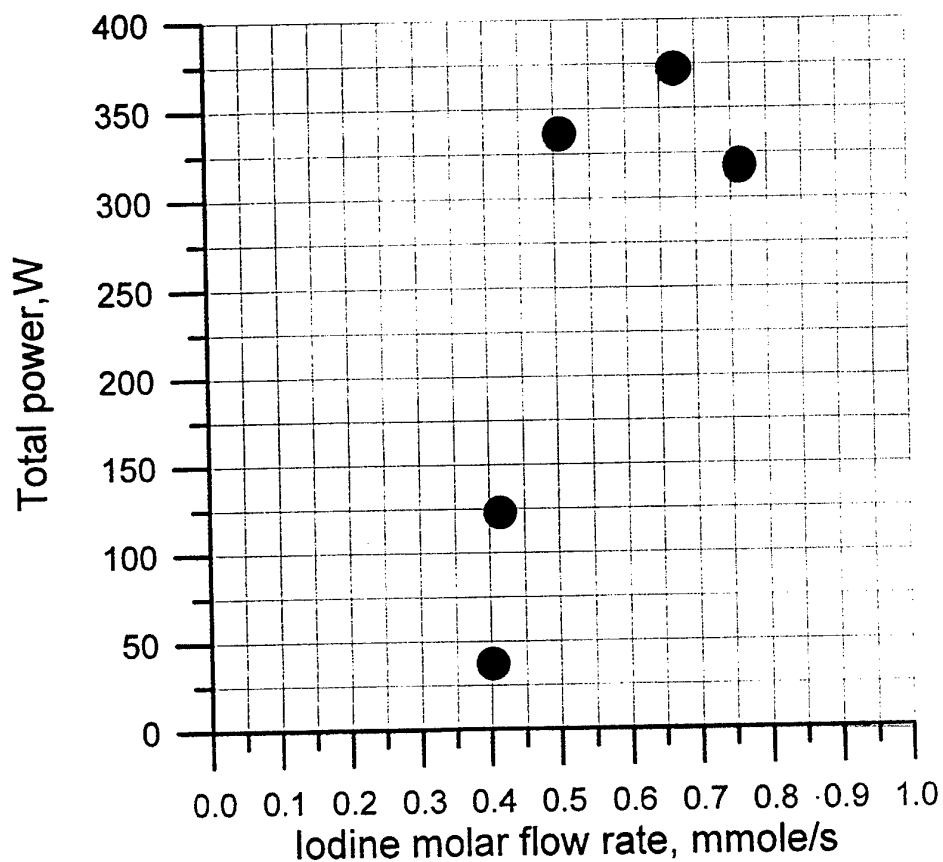
Conditions: optical axis-nozzles 89 mm, chlorine flow rate 39.2 mmole/s, primary nitrogen molar flow rate 400 mmole/s, secondary nitrogen 40 mmole/s, mirror purging 10 mmole/s.





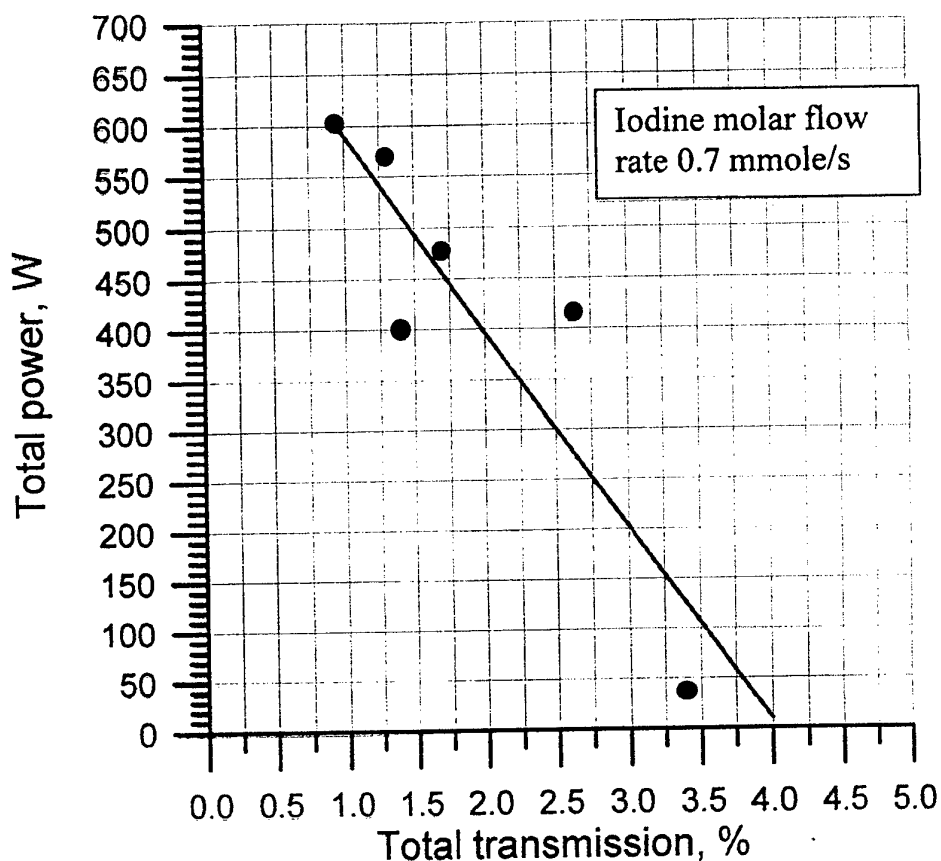
# Dependence of output power on iodine molar flow rate

Conditions: optical axis-nozzles 89 mm, chlorine flow rate 39.2 mmole/s, primary nitrogen molar flow rate 400 mmole/s, secondary nitrogen 40 mmole/s, mirror purging 10 mmole/s, mirrors  $T_1=0.8\%$ ,  $T_2=0.014\%$  (nonresonant losses were unknown)



# Dependence of output power on total mirror transmission

Conditions: optical axis-nozzles 89 mm, chlorine flow rate 39.2 mmole/s, primary nitrogen molar flow rate 400 mmole/s, secondary nitrogen 40 mmole/s, mirror purging 10 mmole/s,



The video of mixing-dissociation zone showed that the length iodine dissociation was shorter 50 mm

Pressures at maximum output power conditions:

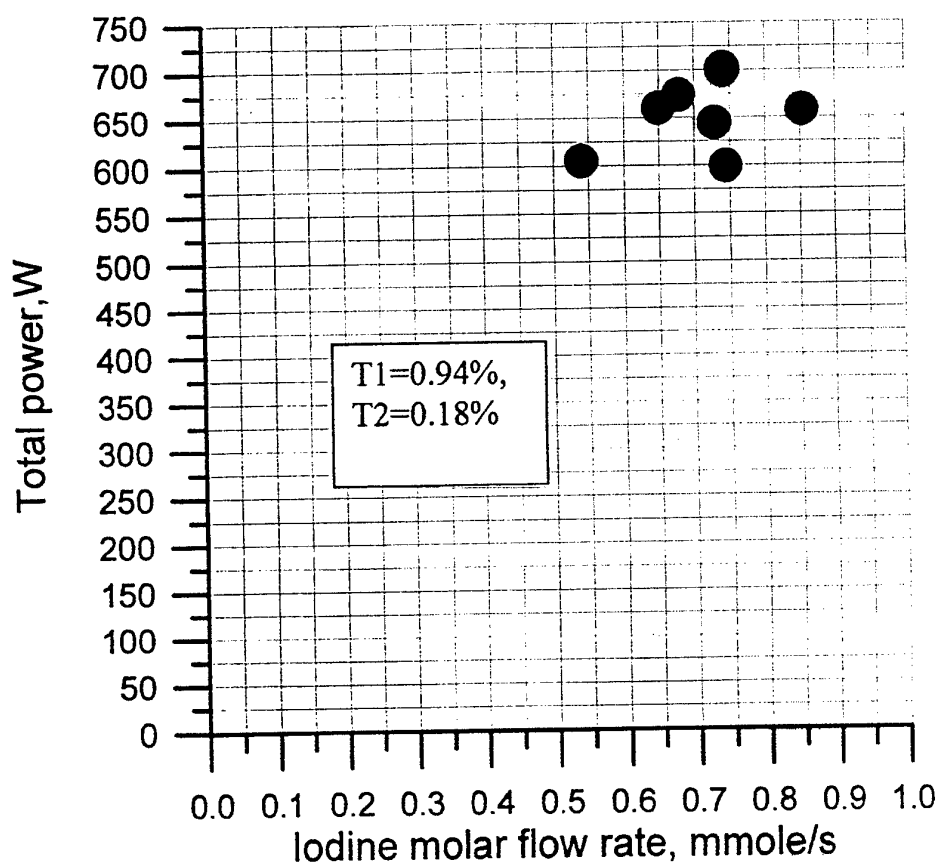
SOG: 41 torr, Plenum : 35.2 torr

Laser cavity: 11.9 torr, Pitot: 81 torr, Mach: 2.2

Total pressure of gas flow in cavity 128 torr

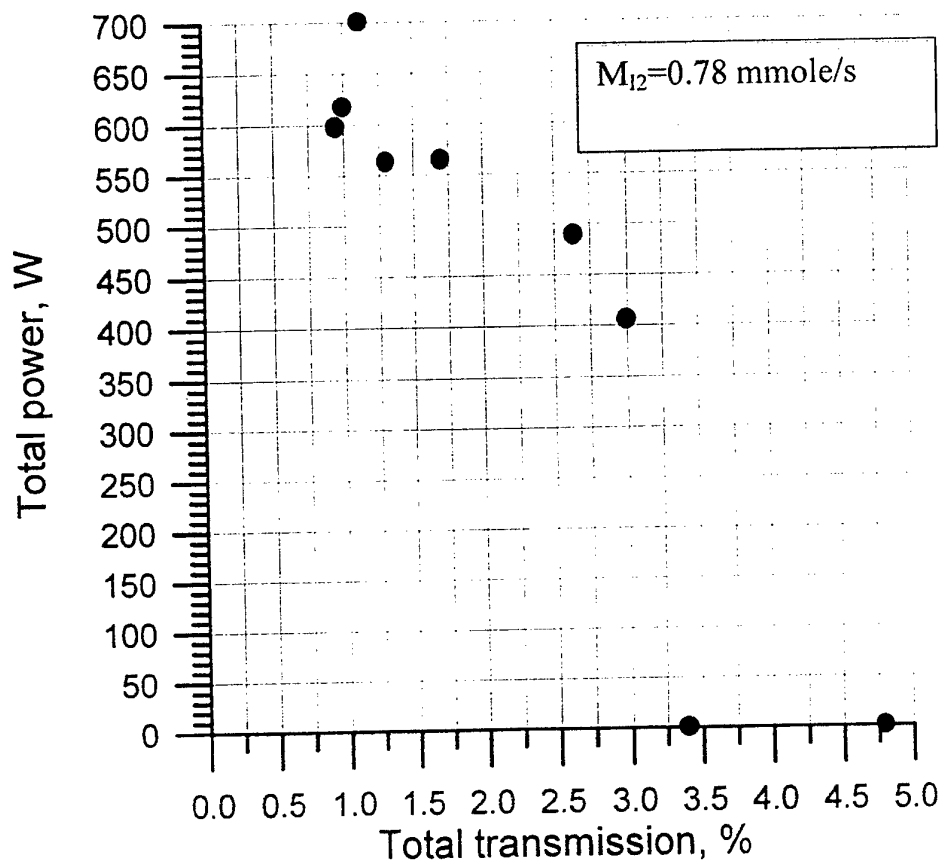
### Dependence of output power on iodine molar flow rate

Conditions: optical axis-nozzles 64 mm, chlorine flow rate 39.2 mmole/s, primary nitrogen molar flow rate 400 mmole/s, secondary nitrogen 40 mmole/s, mirror purging 10 mmole/s,

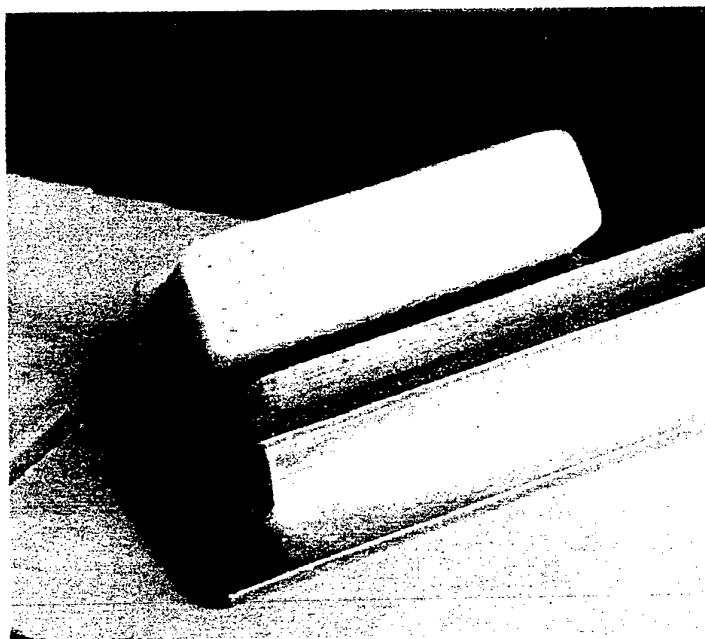
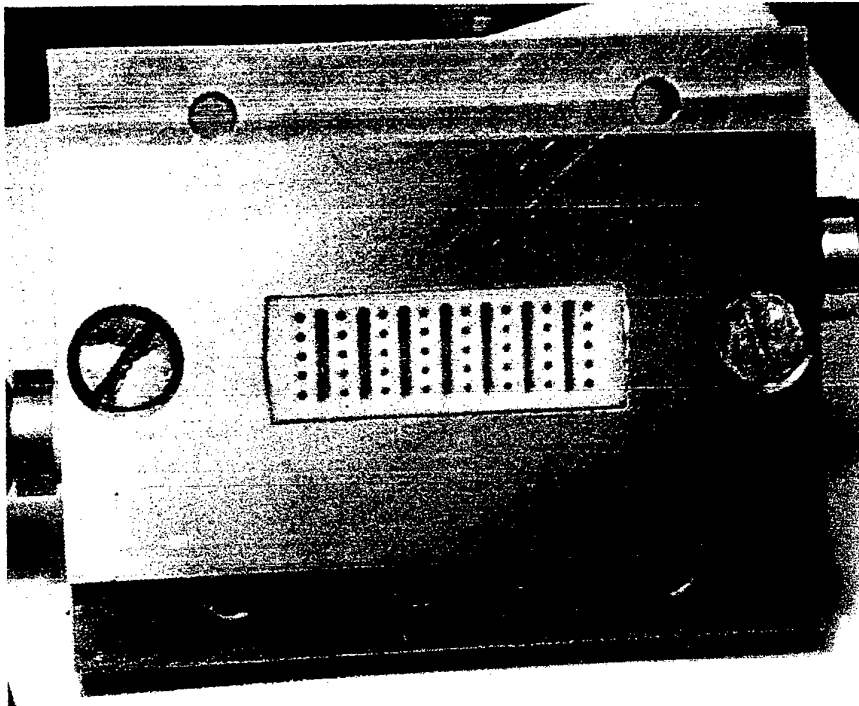


# Dependence of output power on total mirror transmission

Conditions: optical axis-nozzles 64 mm, chlorine flow rate 39.2 mmole/s, primary nitrogen molar flow rate 400 mmole/s, secondary nitrogen 40 mmole/s, mirror purging 10 mmole/s.

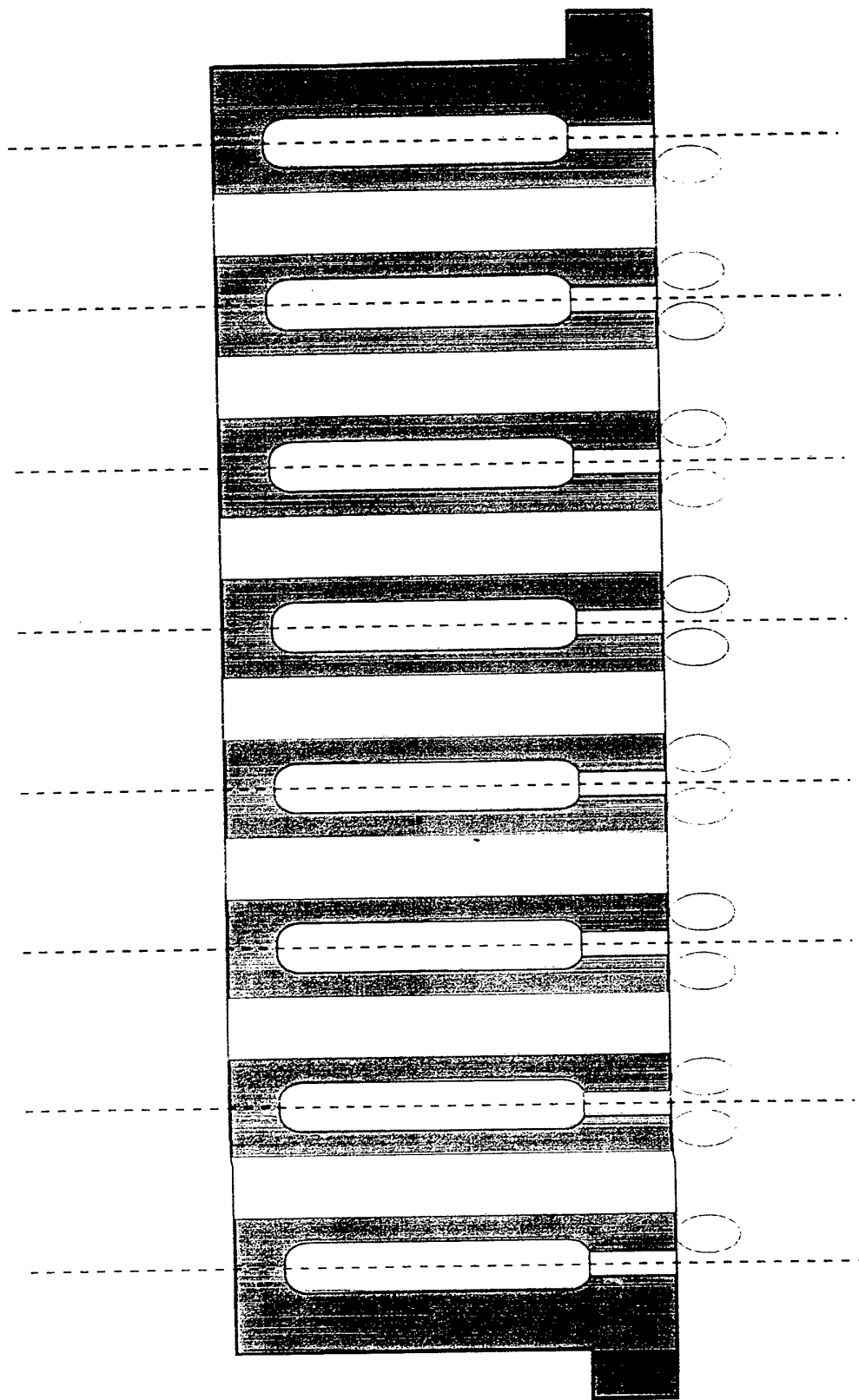


Pressures at maximum output power ( $M_{12} = 0.78$  mmole/s):  
 SOG- 39.4 torr, Plenum- 33 torr, Laser cavity -11.2 torr, Pitot- 101 torr, Mach-2,6.  
 Total pressure of gas flow in laser cavity =218 torr.  
 For  $M_{12} = 0$ , Laser cavity -9.5 torr, Pitot- 98.3 torr, Mach-2,9.  
 Total pressure of gas flow in laser cavity =300 torr.



New ejector grid nozzle

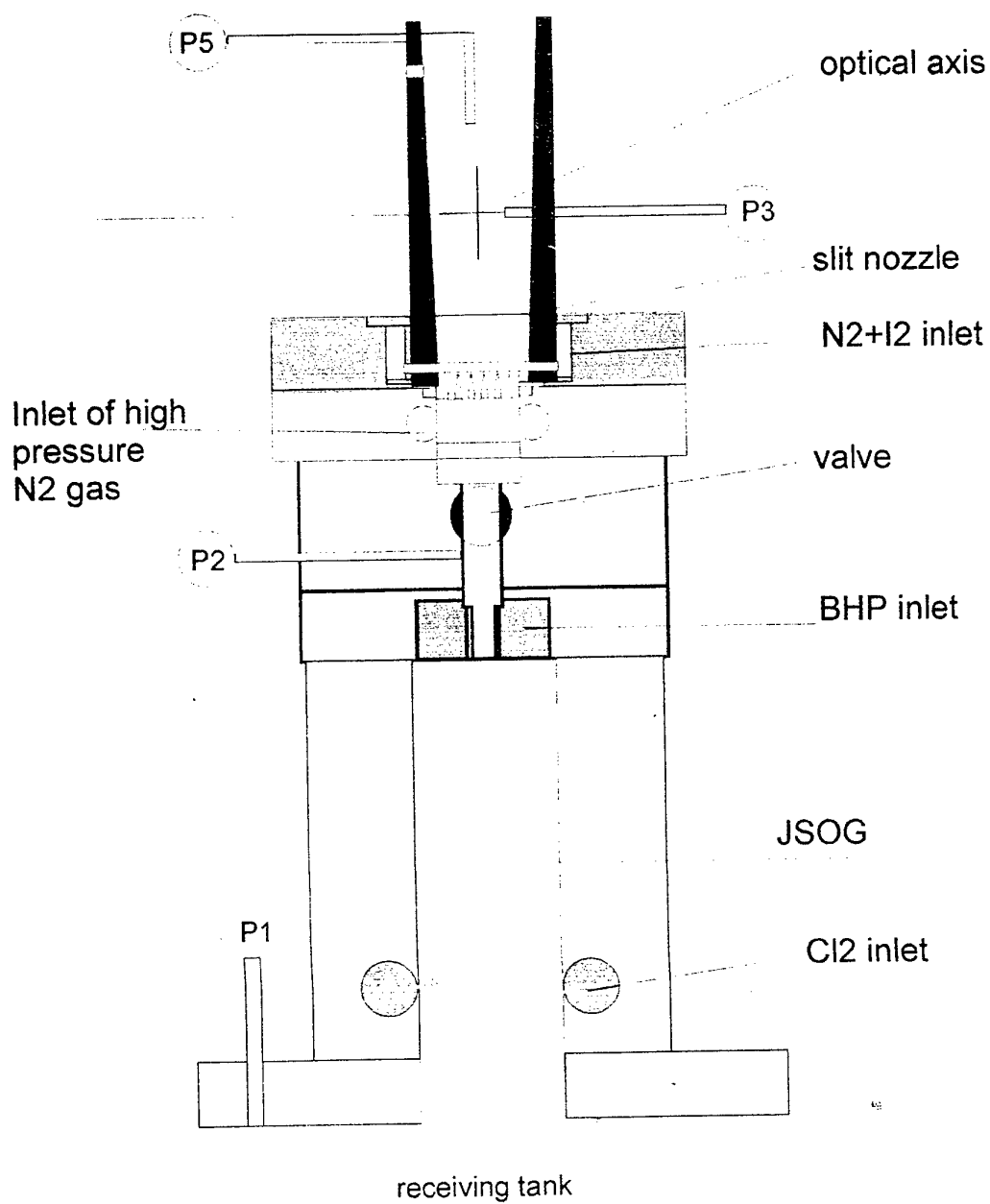
Scale 4:1

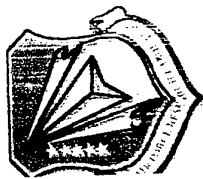


The tubes for iodine injection have i.d. of 2mm and wall thickness of 0.1mm. These tubes have been deformed to elliptical shape with small axis of 1,5mm. 15 orifices of 0.5mm i.d. (one row) were drilled in each tube.

Scale 4:1

The assembly of JSOG with nozzle bank  
(high pressure nitrogen flow mixing with oxygen and  
injection of iodine into boundary layer)





## **A Second Iodine Laser Breakthrough**

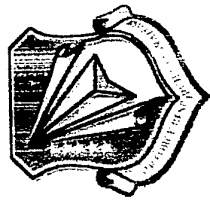
# **Recent Progress in the Development of an All Gas Phase Iodine Laser (AGIL)**

by

Dr. Thomas L. Henshaw, Dr. Timothy J. Madden, Dr. Gerald C. Manke II,  
Dr. John M. Herbelin, Mr. Brian T. Anderson, Mr. Ralph F. Tate,  
and Dr. Gordon D. Hager

**Air Force Research Laboratory/DELC, Kirtland AFB  
3550 Aberdeen Ave. SE  
Kirtland AFB, NM 87117-5776**

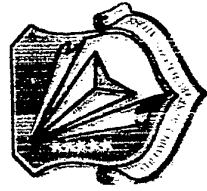




# **At Gas-Phase Iodine Laser Experiment (AGILE) Overview**

---

- 1. Perform direct and quantitative measurement of gain  
resulting from the  $\text{NCl}(a) - \text{I}$  transfer reaction*
- 2. Determine if  $\text{NCl}(a) - \text{I}$  system gain will scale  
with reagent densities*



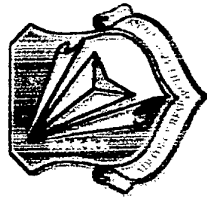
## All Gas-Phase Iodine Laser (AGIL) Overview

- The AGIL system is based on an efficient energy transfer reaction between electronically excited  $\text{NCl}(a^1\Delta)$  metastable molecules and ground state iodine atoms,



- Subsequent lasing is generated on the  $\text{I}^*(^2\text{P}_{1/2}) \rightarrow \text{I}(^2\text{P}_{3/2})$  transition at 1.315  $\mu\text{m}$ :





## NCl( $a^1\Delta$ ) Energetics

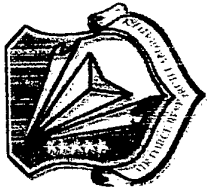
- Interest in NCl( $a^1\Delta$ ) energetics:

- Potential energy carrier in all gas phase I\* laser system
- NCl( $a^1\Delta$ ) metastable isovalent to  $O_2(a^1\Delta)$
- $O_2(a^1\Delta)$  0.98 eV, NCl( $a^1\Delta$ ) 1.1 eV

- Similar I\*( $^2P_{1/2}$ ) Transfer Mechanism:



- *Can NCl(a) be a viable chemical energy substitute for  $H_2O_2$  based COIL?*



## Motivation

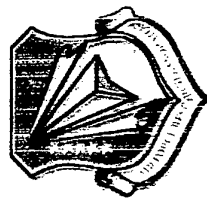
---

### Limitations of COIL in ABL/SBL :

- Aqueous chemistry heavy
- $\text{H}_2\text{O}$  a strong quencher of  $\text{I}^*$
- Heat remains in BHP
- Zero - g

### AGIL a potential chemical substitute for $\text{H}_2\text{O}_2$ -based COIL:

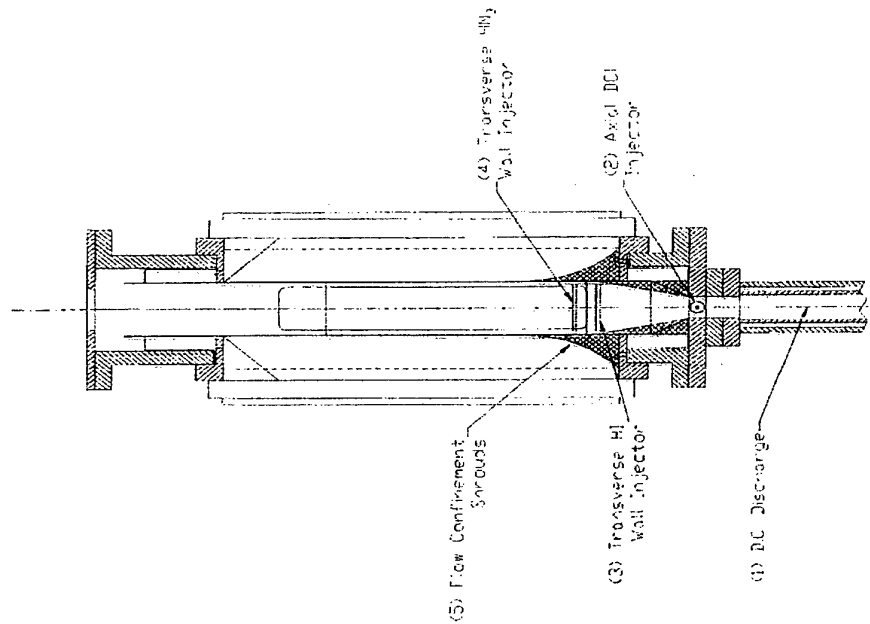
- ✓ purely gas phase reaction, heat rejection in exhaust
- ✓ exhibits higher specific energy content (KJ/Kg)
- ✓ operational in zero-g environments
- ✓ maintains short wavelength, single line lasing



# Chemical Generation of $\text{NCl}(a^1\Delta)$ and $\text{I}^*(2P_{1/2})$

Subsonic Flow Reactor

Chemical Mechanism



## Step 1: $\text{F}, \text{Cl}, \text{I}$ Atom Production:

1.  $\text{F}_2/\text{He} \xrightarrow{\text{dc discharge}} \text{F}, \text{F}_2$
2.  $\text{F} + \text{DCI} \longrightarrow \text{DF} + \text{Cl}, k = 1 \times 10^{-11} \text{ cm}^3/\text{s}$
3.  $\text{Cl} + \text{HI} \longrightarrow \text{HCl} + \text{I}, k = 8 \times 10^{-11} \text{ cm}^3/\text{s}$

## Step 2: $\text{NCl}(a)$ Production:

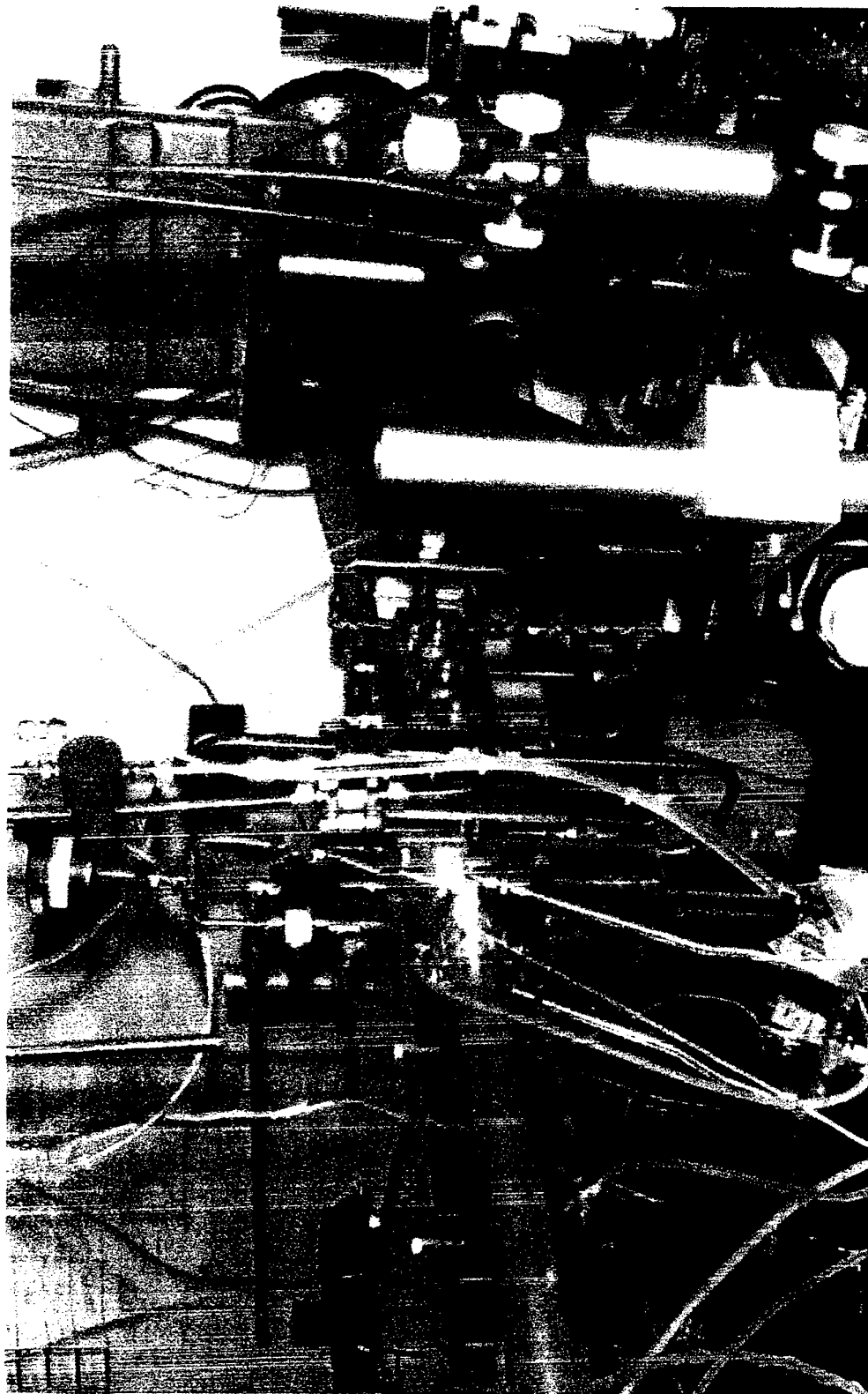
4.  $\text{Cl} + \text{HN}_3 \longrightarrow \text{HCl} + \text{N}_3, k = 1 \times 10^{-12} \text{ cm}^3/\text{s}$
5.  $\text{Cl} + \text{N}_3 \longrightarrow \text{NCl}(a) + \text{N}_2, k = 2 \times 10^{-11} \text{ cm}^3/\text{s}$

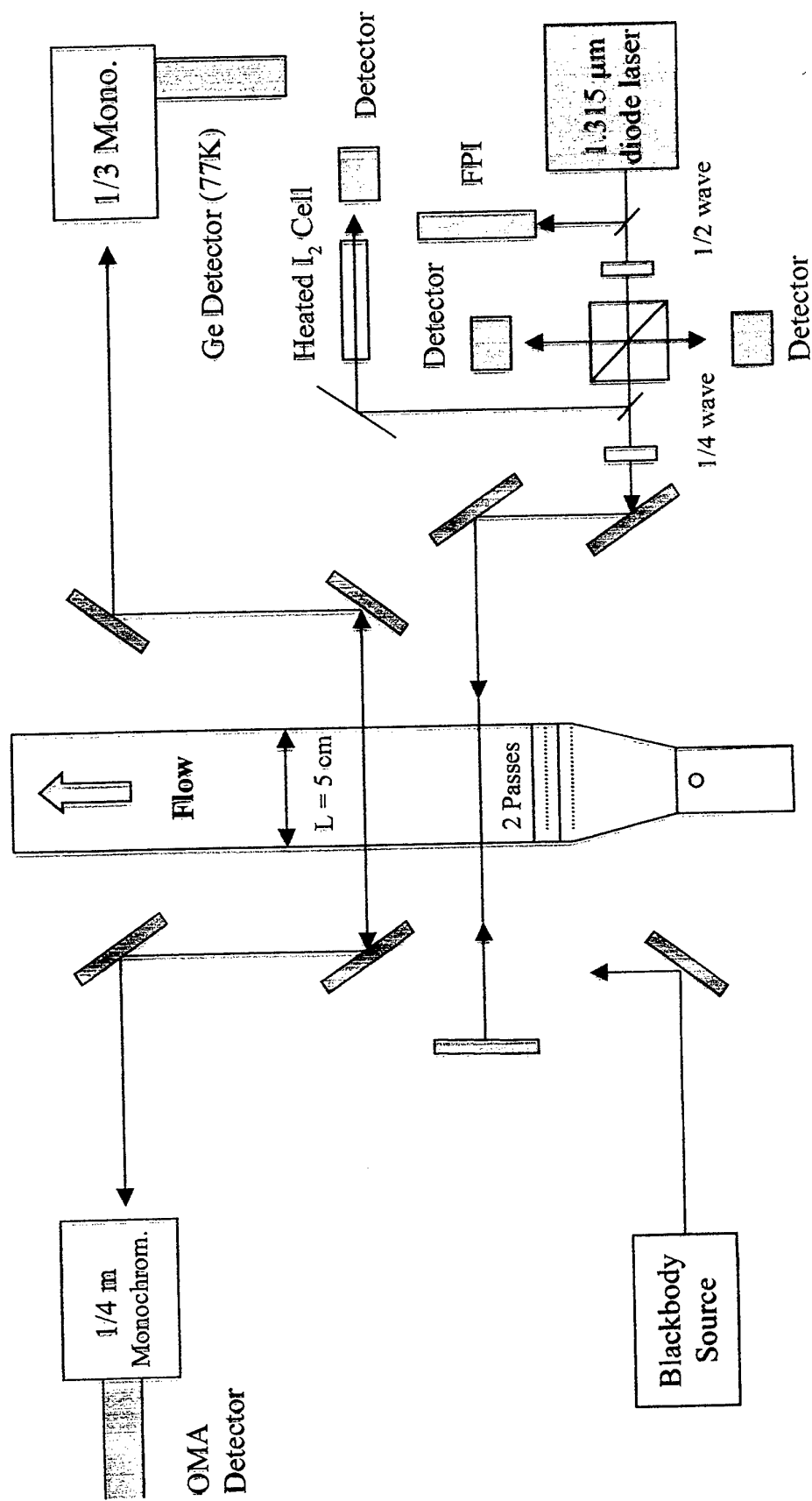
## Step 3: $\text{I}^*$ Production:

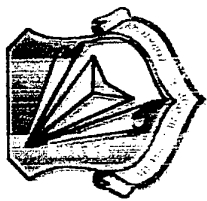
6.  $\text{NCl}(a) + \text{I} \longrightarrow \text{I}^* + \text{NCl}(X), k = 2 \times 10^{-11} \text{ cm}^3/\text{s}$



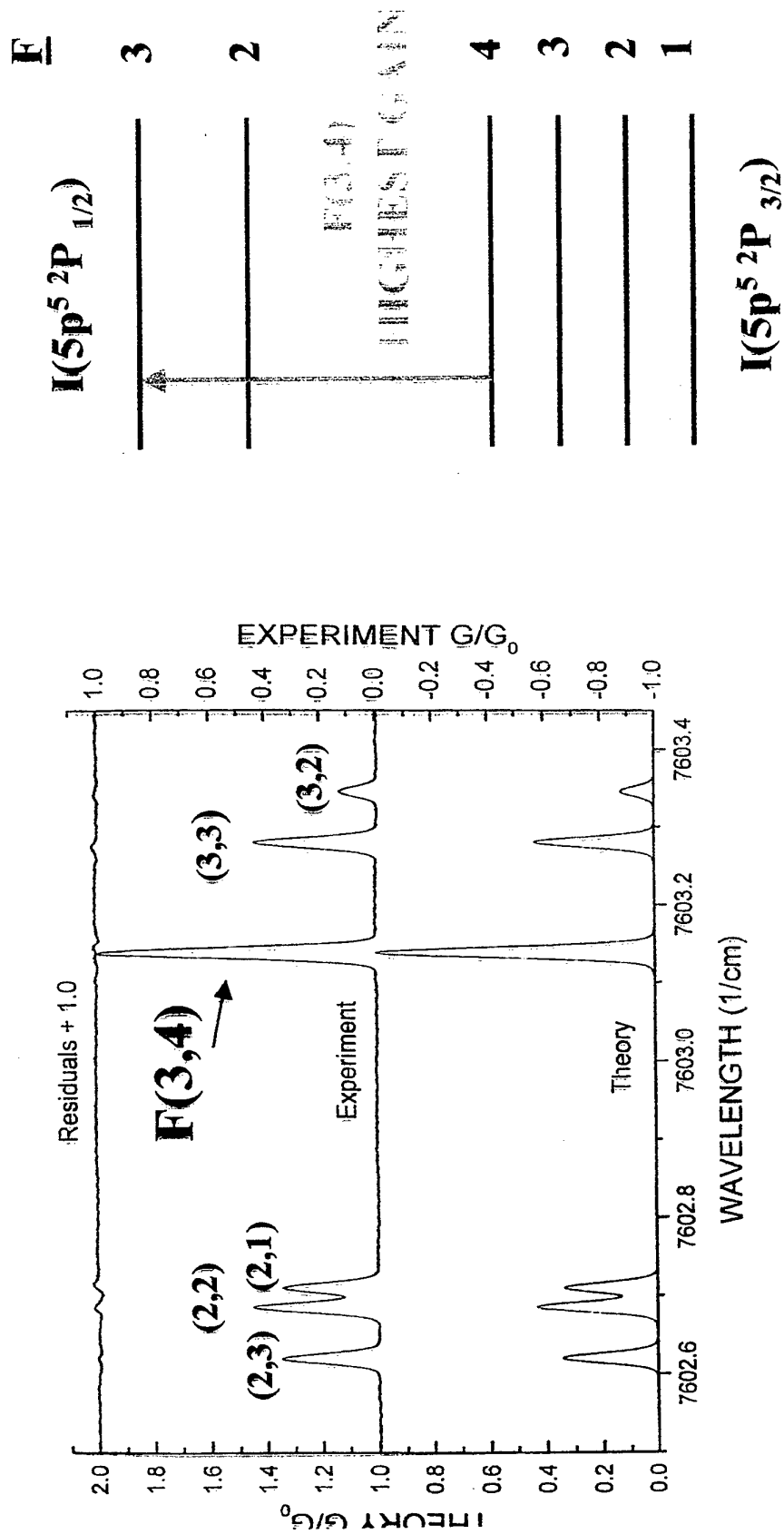
# AGIL SUBSONIC FLOW APPARATUS



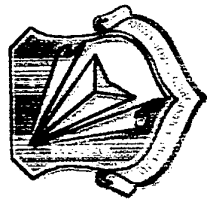




# ATOMIC IODINE HYPERFINE SPECTRUM







# Absorption Line Shape Analysis

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$$I = I_0 \exp(\gamma L), \quad \gamma = \sigma \Delta N, L = 10 \text{ cm}$$

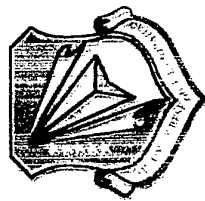
$$I(\nu) = I_0(\nu) \exp(\sigma(\nu) \Delta N L)$$

$$\sigma(\nu) = \frac{A_{3,4} \lambda^2}{8\pi} f(\nu), \quad f(\nu) = \text{Voigt Line Function}$$

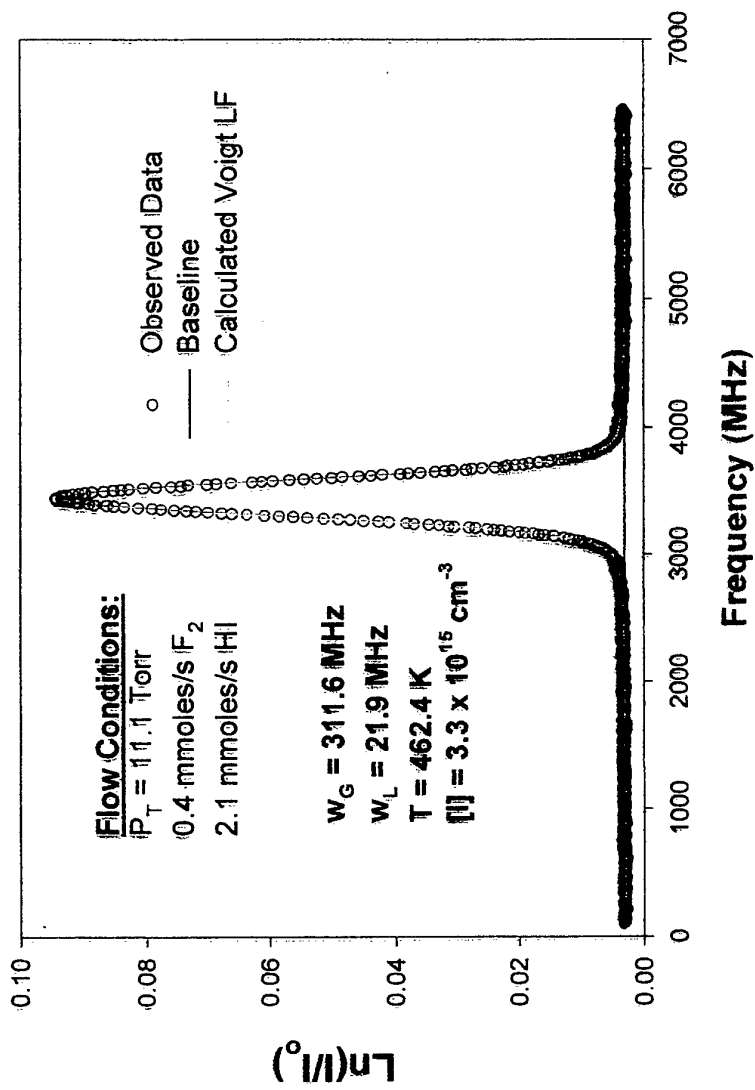
$$\Delta N = \left( N_u - \frac{g_u}{g_l} N_l \right) = \left[ \frac{7}{12} \left( I^* - \frac{1}{2} I \right) \right]$$

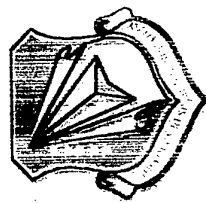
$$\int_{-\infty}^{\infty} \gamma(\nu) d\nu = \text{Area} = \frac{A_{3,4} \lambda^2}{8\pi} \int_{-\infty}^{\infty} f(\nu) d\nu \left[ \frac{7}{12} \left( I^* - \frac{1}{2} I \right) \right] L$$

$$\text{where } \int_{-\infty}^{\infty} f(\nu) d\nu \equiv 1$$



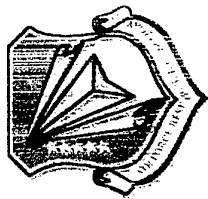
# Absorption Spectrum of $I(^2P_{3/2}), F(3,4)$





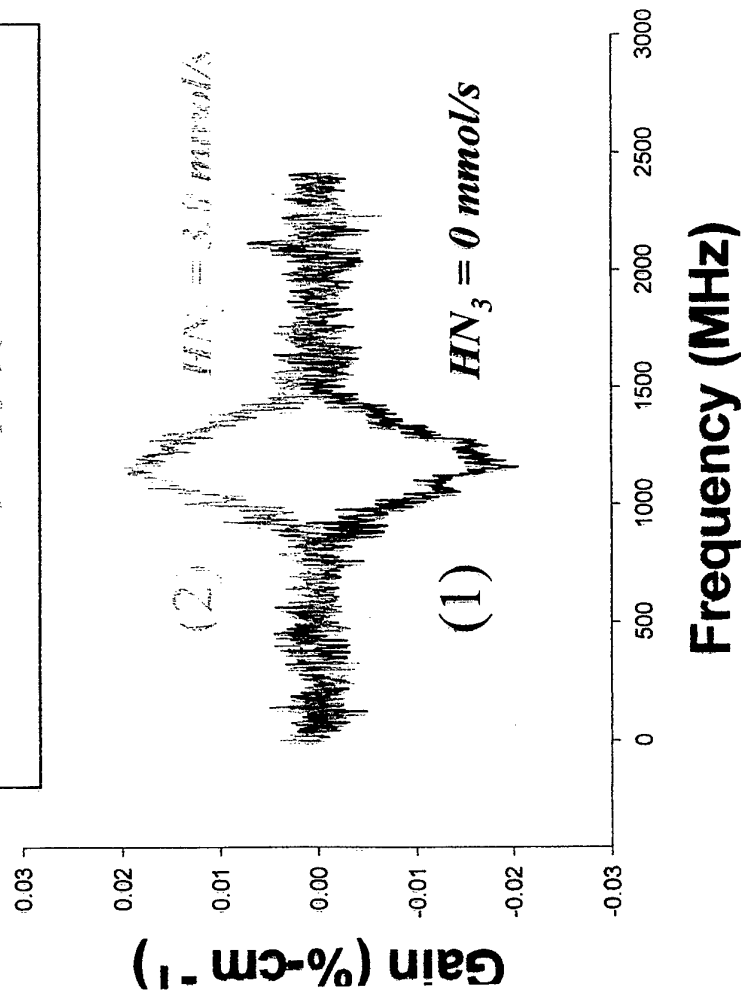
# Nominal Flow Parameters for $I^*$ Gain Measurement

Reagent	Molar Flow	Reactor Pressure,	Reagent Density,	Cross Sectional	Flow Velocity,	Flow Temperature,
Species	Rate,	Torr	$\text{cm}^{-3}$	Area, $\text{cm}^2$	$\text{cm/s}$	$^{\circ}\text{K}$
He	151.28	15.50	$3.0 \times 10^{17}$	10	$2.9 \times 10^4$	470
$\text{F}_2$	0.66		$1.3 \times 10^{15}$			
$\text{DCI}$	2.00		$4.0 \times 10^{15}$			
$\text{HN}_3$	3.32		$6.6 \times 10^{15}$			
HI	0.032		$6.3 \times 10^{13}$			
Total	157.29		$3.1 \times 10^{17}$			



# Direct Measurement of $I^+(2P_{1/2})$ Gain

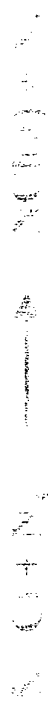
$P_2 = 0.6$ ,  $P_{DCI} = 2.0$ ,  $IHI = 0.04$  mmole/s  
 $P = 16$  Torr

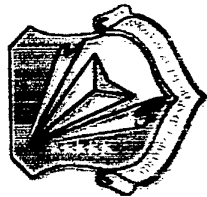


## Curve 1: Absorption:



## Curve 2: Gain

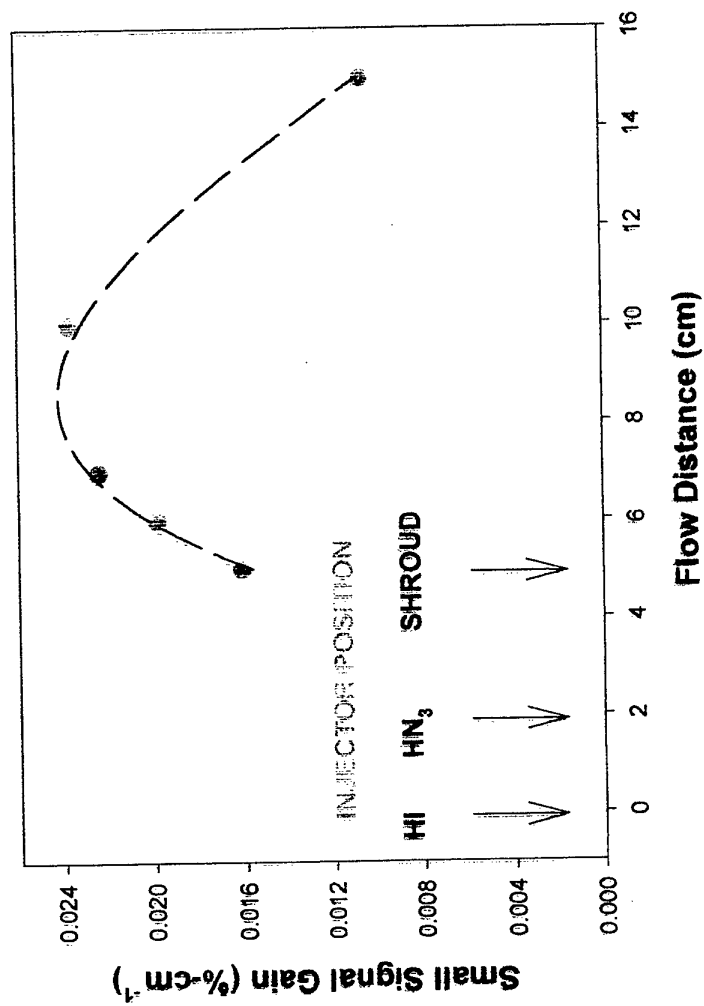


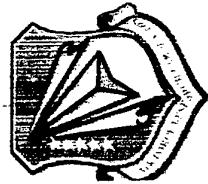


# SSG Gain Profile



$F_2 = 0.75 \text{ mmole/s}$  (85% dissociated),  $\text{DCI} = 2.0 \text{ mmole/s}$ ,  $\text{HI} = 0.039 \text{ mmole/s}$   
 $\text{HN}_3 = 4.0 \text{ mmole/s}$ ,  $P = 16 \text{ torr}$

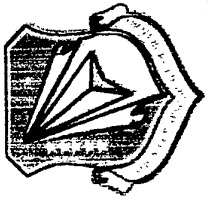




# Kinetic Modeling

## Key Rates of $\text{NCl}(a^1\Delta) + \text{I}$ Model

$\text{F} + \text{DCI} \rightarrow \text{DF} + \text{CI}$	$1.6 \cdot 10^{-11}$	Based on $\text{F} + \text{HCl}$ ; Nip and Clyne (1977)
$\text{Cl} + \text{F} + \text{N}_2 \rightarrow \text{HCl} + \text{N}_2$	$8.9 \pm 1.2 \cdot 10^{-13}$	Yamasaki et al, Chem. Phys. Lett., <b>94</b> , 425, (1983) Manke and Setser, J. Phys. Chem, <b>102</b> , 153, (1998) Manke et al. Chem. Phys. Lett. 310, 111 (1999).
$\text{Cl} + \text{N}_2 \rightarrow \text{NCl}(a) + \text{N}_2$	$2.0 \cdot 10^{-10} \exp(-1452/\text{T})$	Henshaw et al, J. Phys. Chem., <b>102</b> , pp 6239, (1998) Manke and Setser, (1998)
$\text{Cl} + \text{N}_2 \rightarrow \text{NCl}(b) + \text{N}_2$	$2.25 \cdot 10^{-11}$	
$\text{Cl} + \text{N}_2 \rightarrow \text{NCl}(x) + \text{N}_2$	$0.75 \cdot 10^{-11}$	
$\text{Cl} + \text{N}_2 \rightarrow \text{NCl}(b) + \text{N}_2$	$1 \cdot 10^{-14}$	
$2\text{N}_3 \rightarrow 3\text{N}_2$	$3 \cdot 10^{-12}$	David and Coombe. J. Phys. Chem., <b>90</b> , 3260 (1986)
$2\text{NCl}(x) \rightarrow \text{N}_2 + 2\text{Cl}$	$8.1 \pm 1.8 \cdot 10^{-12}$	Clyne and MacRobert, J. Chem. Soc. Faraday Trans. 2, <b>79</b> , pp283-293, (1983)
$\text{NCl}(a) + \text{I} \rightarrow \text{NCl}(x) + \text{I}^*$	$1.8 \cdot 10^{-11}$	Ray and Coombe, J. Phys. Chem., <b>97</b> , 3476, 1993
	$1.1 \cdot 10^{-10} \exp(-519\text{K}/\text{T})$	Henshaw et al, J. Phys. Chem., <b>102</b> , pp 6239, (1998)
$2\text{NCl}(a) \rightarrow \text{NCl}(b) + \text{NCl}(x)$	$1.5 \cdot 10^{-13}$	Manke and Setser, (1998)
$2\text{NCl}(a) \rightarrow \text{products}$	$7.2 \pm 0.9 \cdot 10^{-12}$	Henshaw et al, J. Phys. Chem., <b>101</b> , pp 4048, (1997)
$2\text{NCl}(a) \rightarrow \text{N}_2 + 2\text{Cl}$	$6.8 \cdot 10^{-12}$	

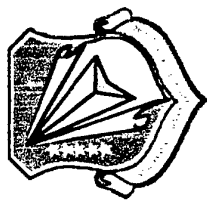


# Previous Gain Demonstration

- Yang, Gyllys, Bower, Rubin (1992):  
Gain in Flow Reactor
  - Ray and Coombe (1995): Pulsed  
photolytic laser demonstration
- |              |                   |                |                         |                   |                                   |
|--------------|-------------------|----------------|-------------------------|-------------------|-----------------------------------|
| $F + DCl$    | $\longrightarrow$ | $DF + Cl$      | $CIN_3 + h\nu$          | $\longrightarrow$ | $NCl(a) + N_2$                    |
| $Cl + ICl$   | $\longrightarrow$ | $Cl_2 + I$     | $CH_2I_2 + h\nu$        | $\longrightarrow$ | $CH_2I + I$                       |
| $Cl + HN_3$  | $\longrightarrow$ | $HCl + N_3$    | $NCl(a) + I$            | $\longrightarrow$ | $I^* + NCl(X)$                    |
| $Cl + N_3$   | $\longrightarrow$ | $NCl(a) + N_2$ | $I + CIN_3$             | $\longrightarrow$ | $I + NCl(a) + N_2$                |
| $NCl(a) + I$ | $\longrightarrow$ | $I^* + NCl(X)$ | $NCl(a) + CIN_3$        | $\longrightarrow$ | $NCl(a, X) + N_2(X, v)$           |
|              |                   |                | $N_2(X, v > 0) + CIN_3$ | $\longrightarrow$ | $NCl(a) + 2N_2(X, v=0)$           |
|              |                   |                | $I^* + nh\nu$           | $\longrightarrow$ | $I + 1.315 \mu m \text{ (laser)}$ |

- $I^*(^2P_{1/2})$  gain measured *indirectly* via  
double resonance technique
- complex chemistry,  $I^*(^2P_{1/2})$  inversion  
generated via *chain decomposition* of  
 $CIN_3$ , sensitive to  $N_2(v)$

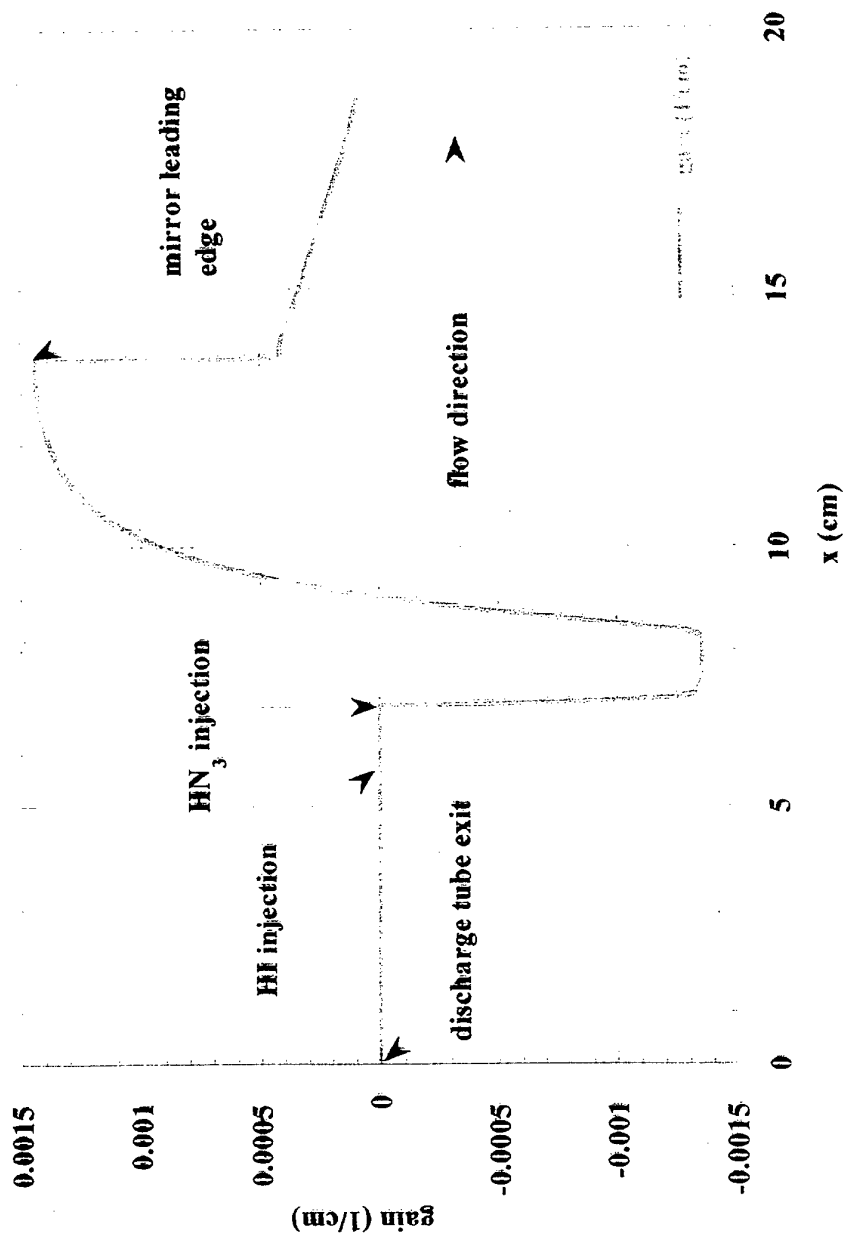
- Both measurements near threshold conditions  
quantitative measurements difficult



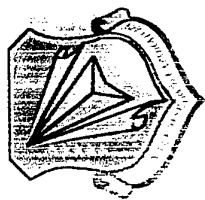
# Model Calculation of Subsonic SSG Scaling

Gain v. Streamwise Distance from Discharge Tube - Laser Demo Hardware  
 $[F] = 8 \text{ mmole/s}$ ,  $[DCI] = 20 \text{ mmole/s}$ ,  $[HN_3] = 5 \text{ mmole/s}$ ,  $[HI] = 1.2 \text{ mmole/s}$ ,

$P = 28 \text{ torr}$ ,  $T = 950 \text{ K}$





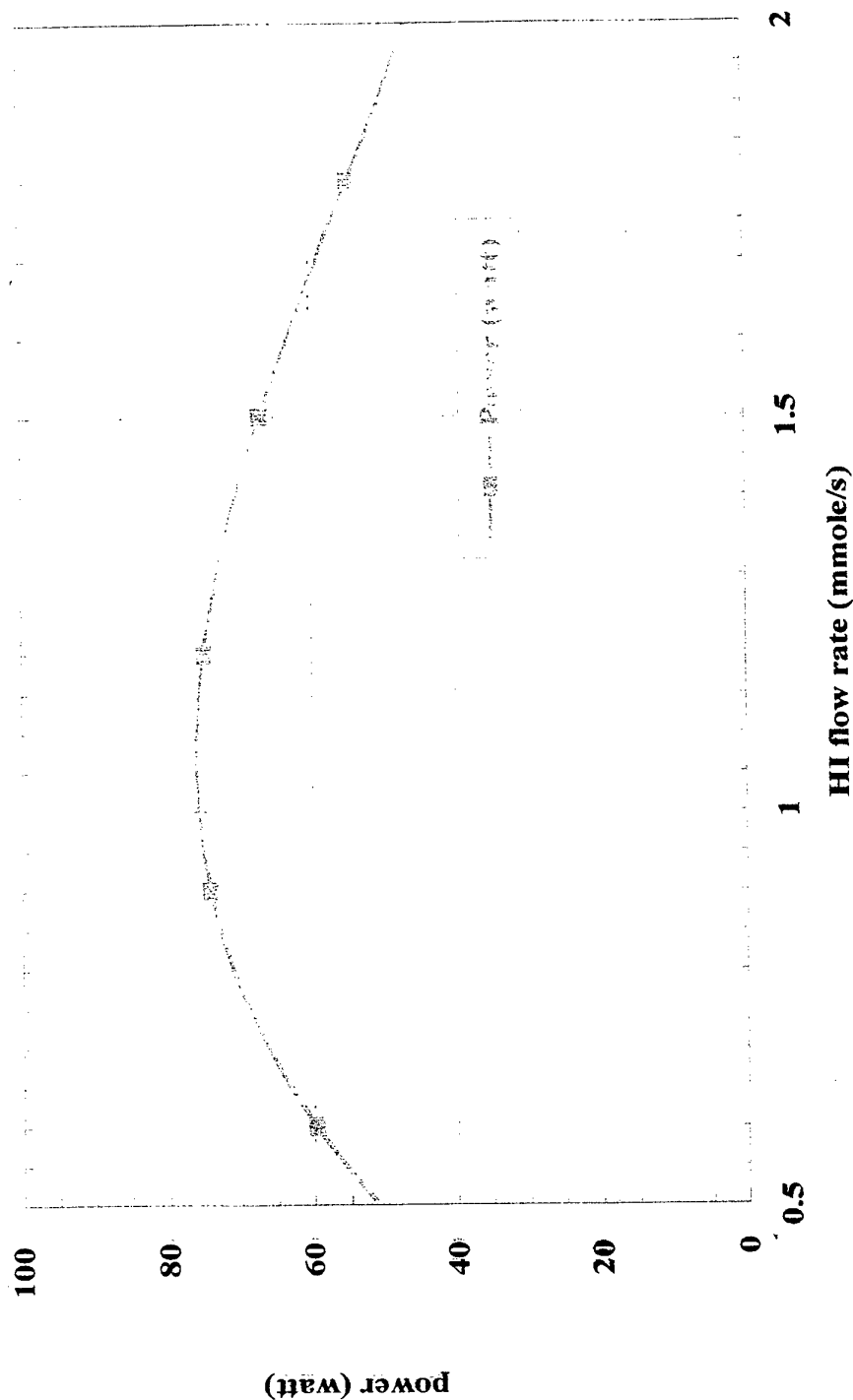


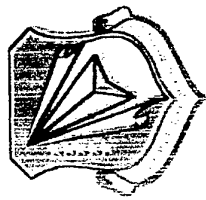
# Model Calculation of Subsonic Laser Power Scaling

## Power v. HI Flow Rate - Laser Demo Hardware

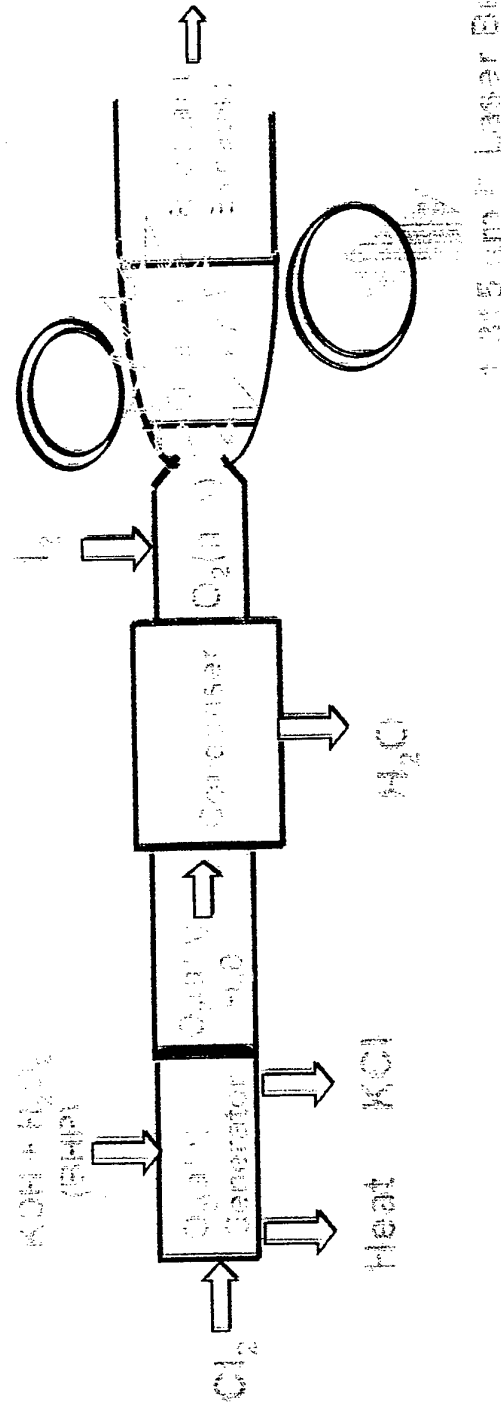
[F] = 8 mmole/s, [DCI] = 20 mmole/s, [HN<sub>3</sub>] = 5 mmole/s,

P = 28 torr, T = 950 K, Mirror Reflectivity = 0.99, Mirror Length = 5 cm





# The COIL Laser

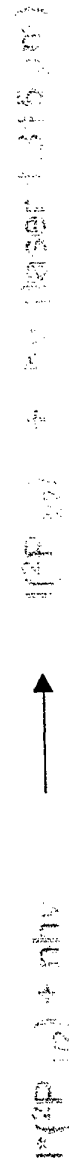


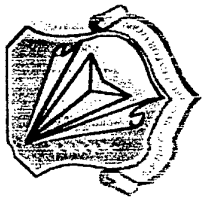
## The CHEMICAL OXYGEN IODINE LASER, COIL

- Based on chemical production of  $O_2(a^1\Delta)$  metastables
- $O_2(a^1\Delta)$  produced from heterogeneous  $KOH/H_2O_2/Cl_2$  mixtures:

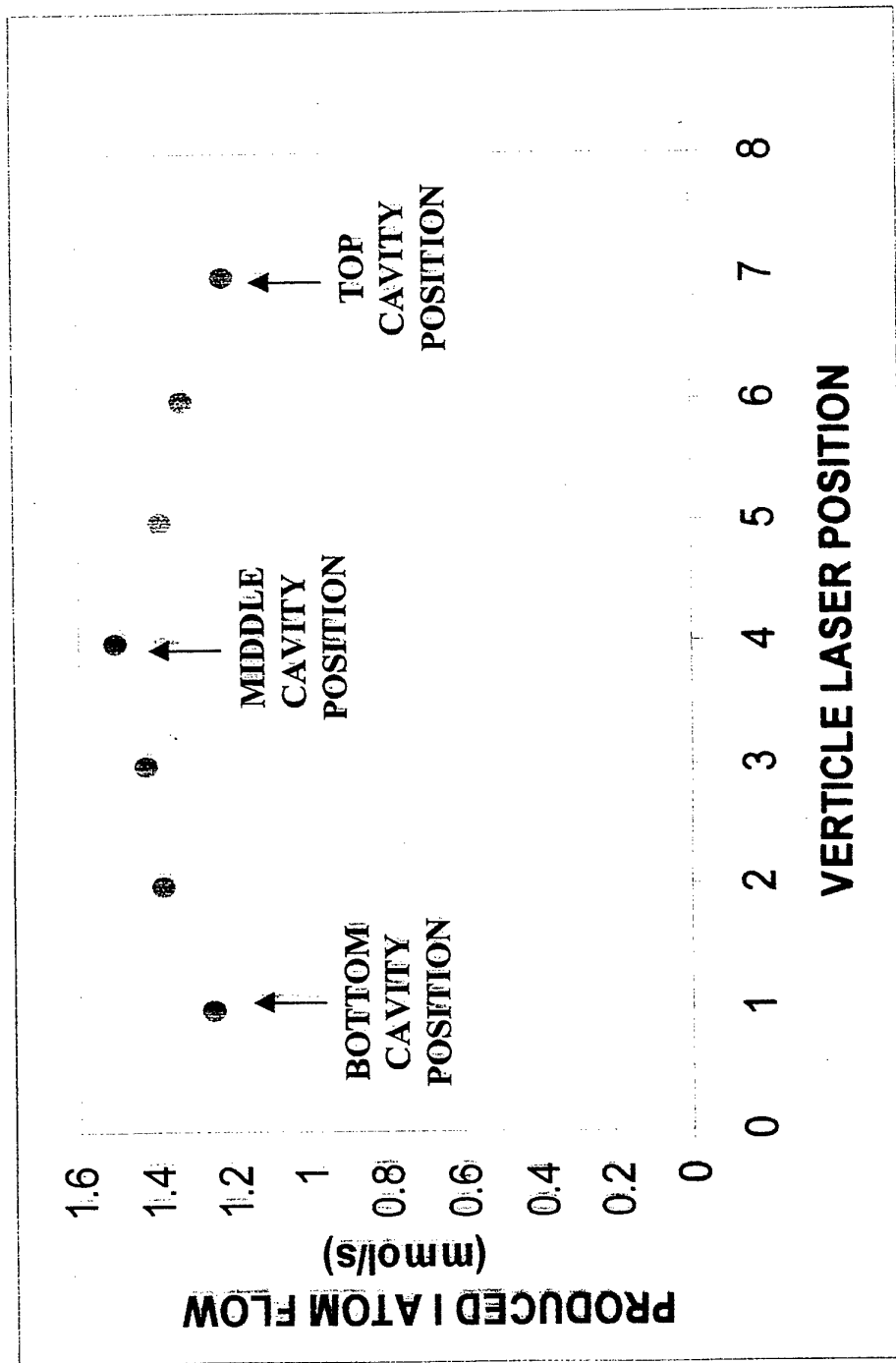


## Energy Transfer and Laser:



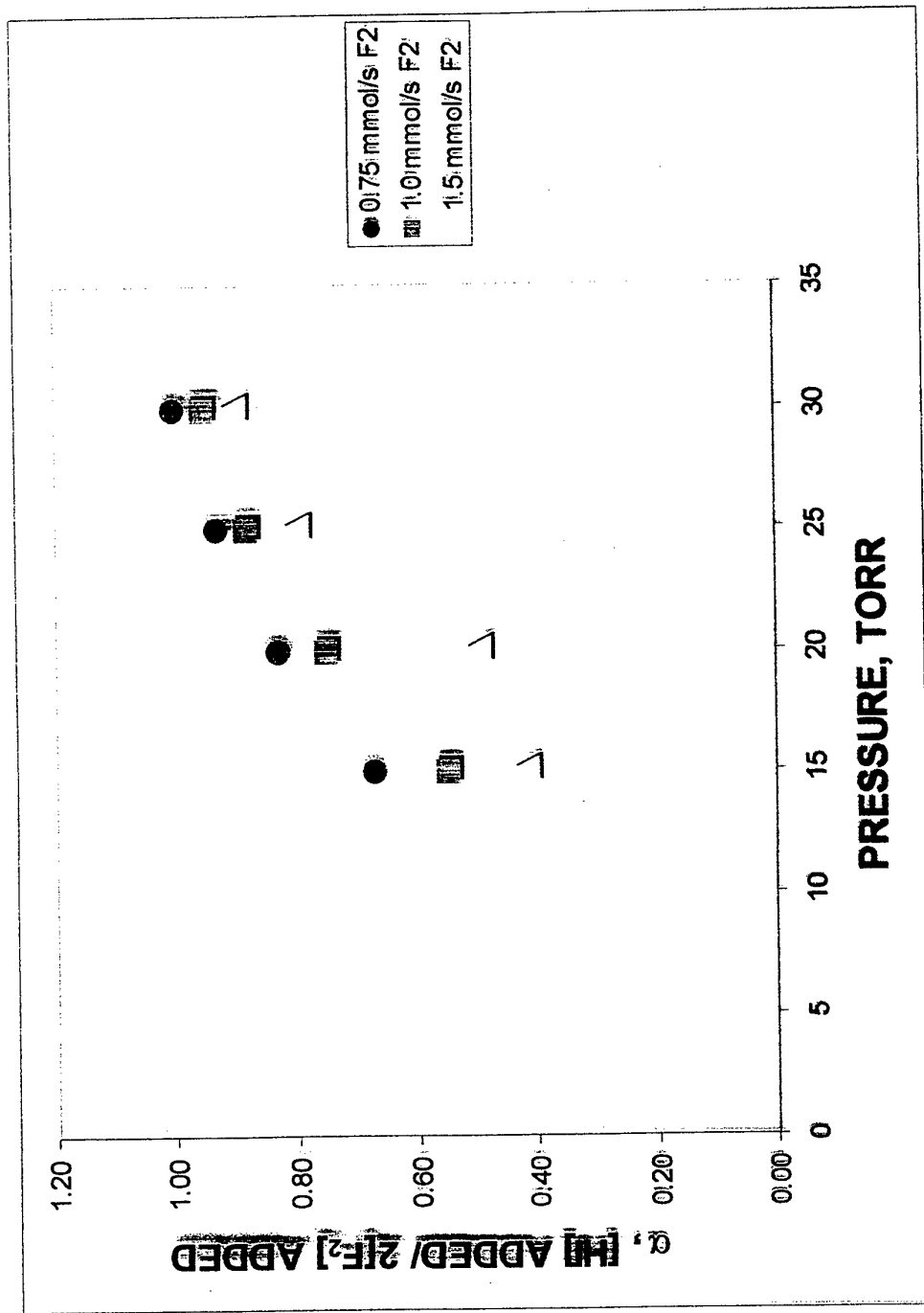


# 2D SPATIAL CAVITY SCAN OF I ATOM FLOW



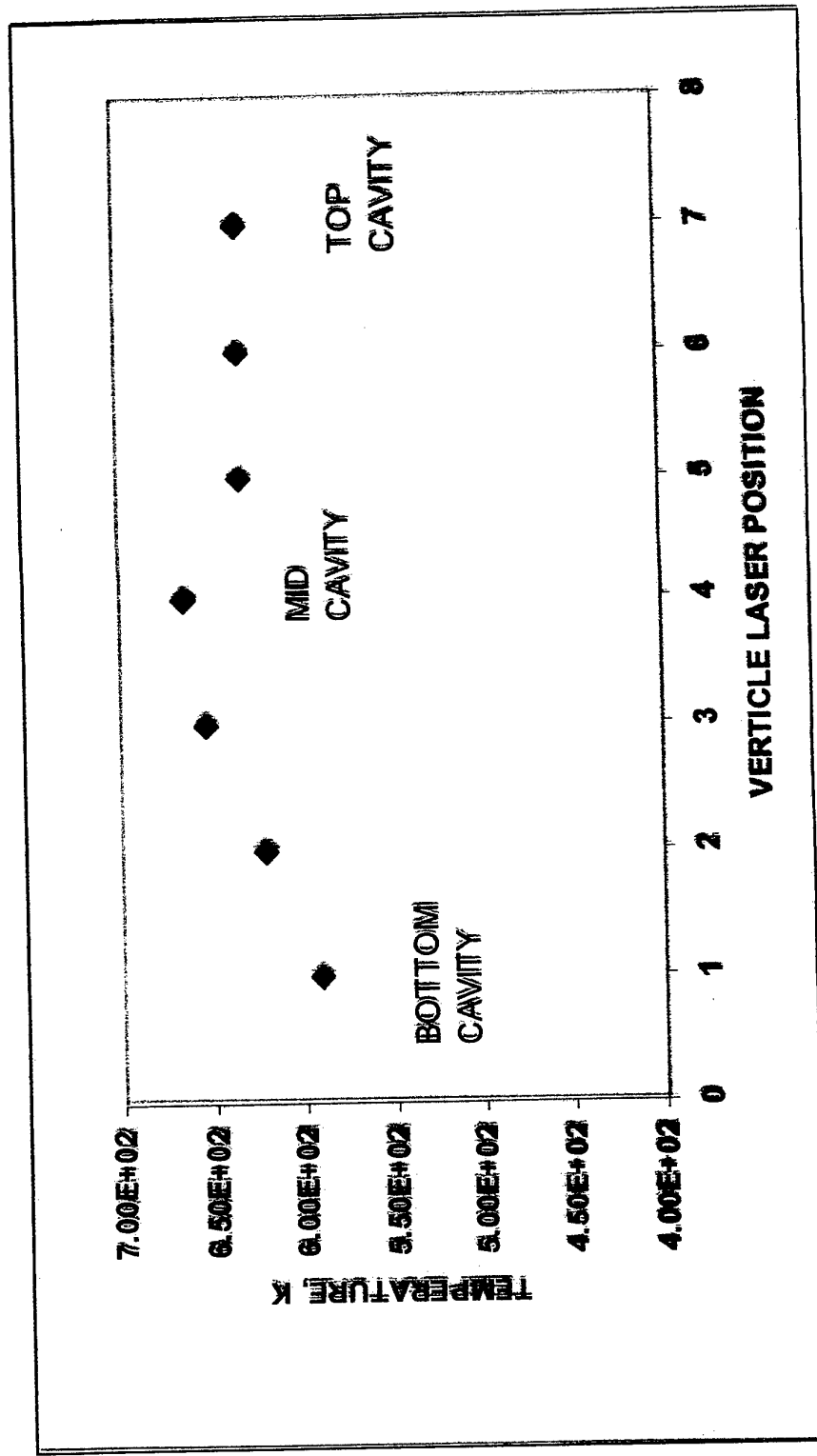


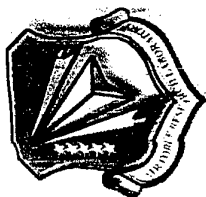
# SCALING OF CONVERSION EFFICIENCY, $\alpha$ , WITH PRESSURE, $z = 6$ cm, $i = 2.75$ A





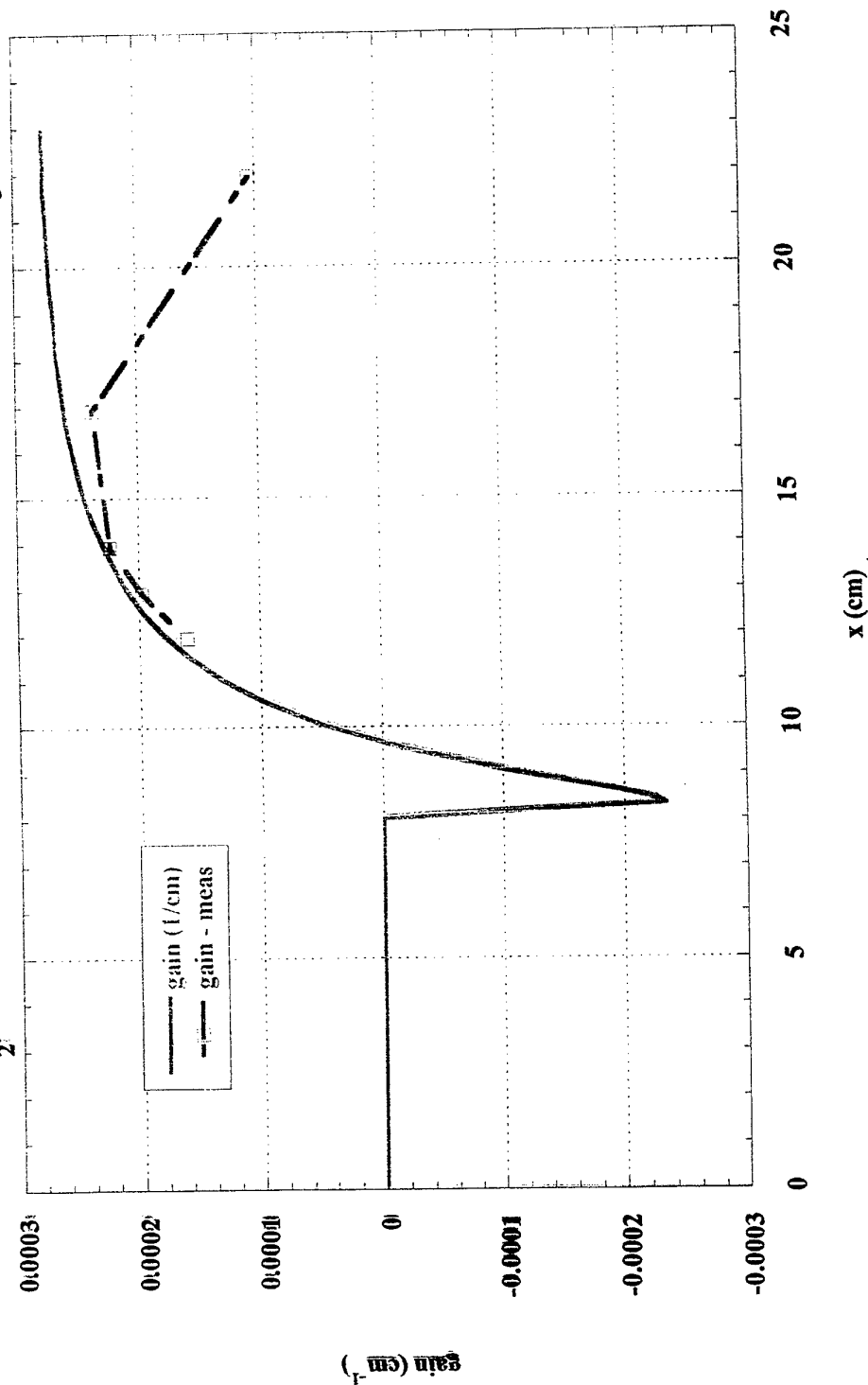
# 2D TEMPERATURE SCAN OF CAVITY FLOW FIELD

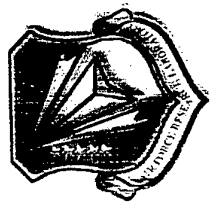




# Comparison of Model and Experiment

Comparison of Gain from  $\text{NCl(A)}_2$  Model and Experiment  
 $0.75 \text{ mmol/s } \text{F}_2$ ,  $2.0 \text{ mmol/s } \text{DCl}$ ,  $0.039 \text{ mmol/s } \text{HCl}$ ,  $4.0 \text{ mmol/s } \text{HN}_3$ ,  $P = 16 \text{ torr}$



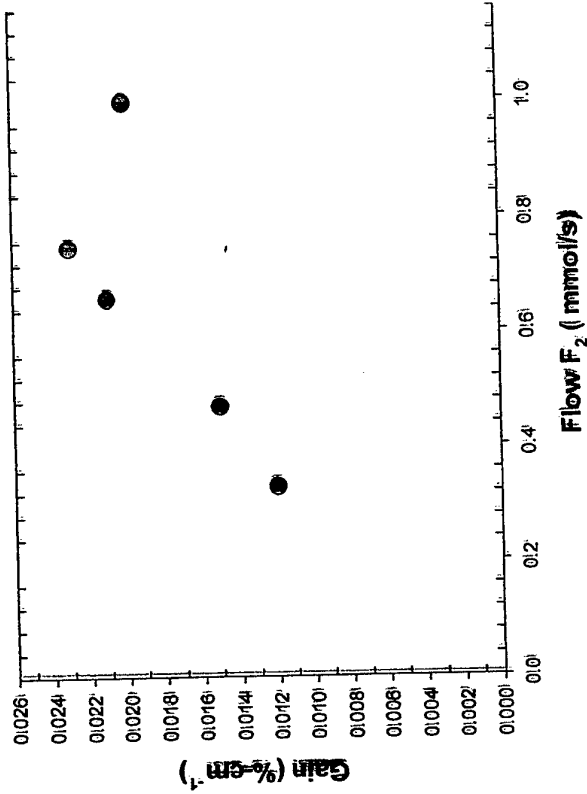
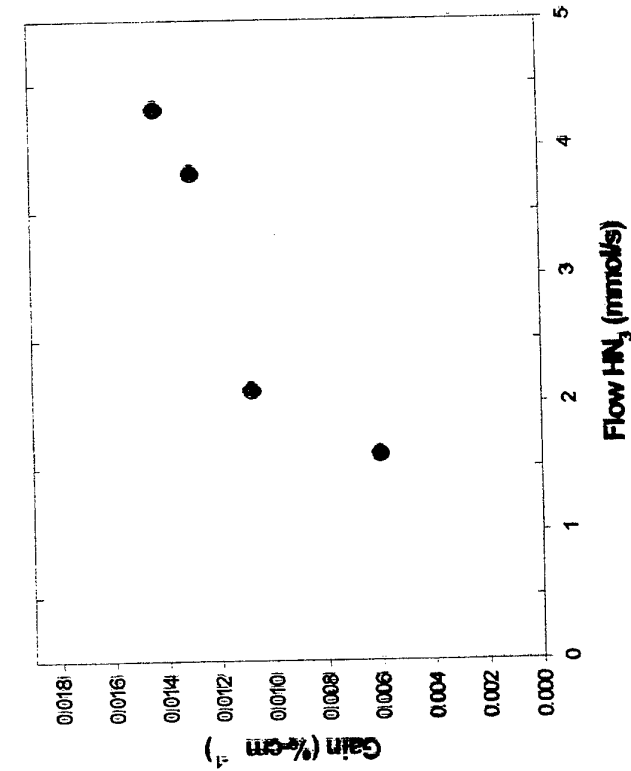


# SSG Scaling with Reagent Flow

**P = 16 Torr**

**DCI = 2.0, HI 0.03,  $\text{HN}_3$  = 4.5 mmole**

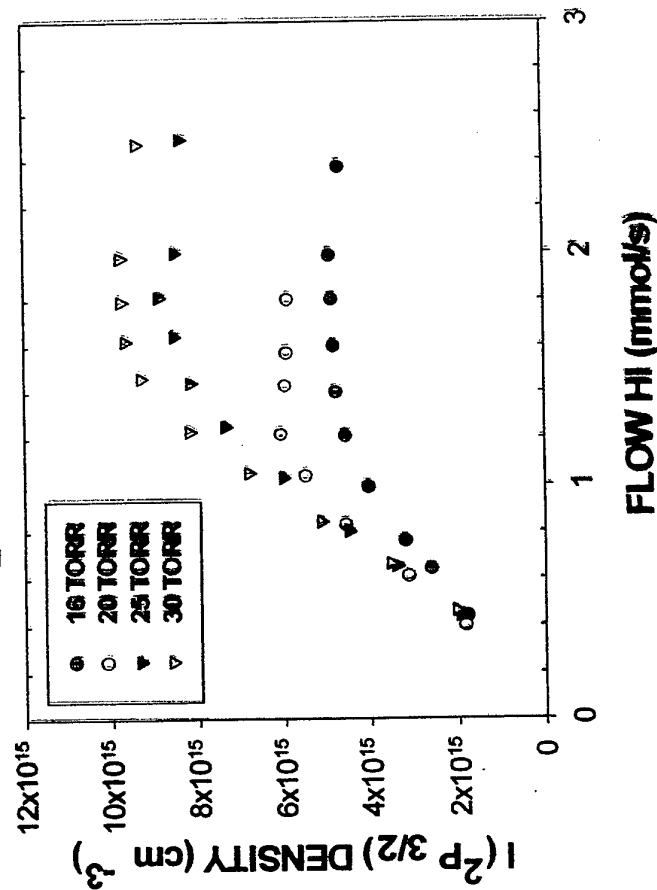
**$F_2$  = 0.5, DCI = 2.0, HI 0.03 mmole/s**



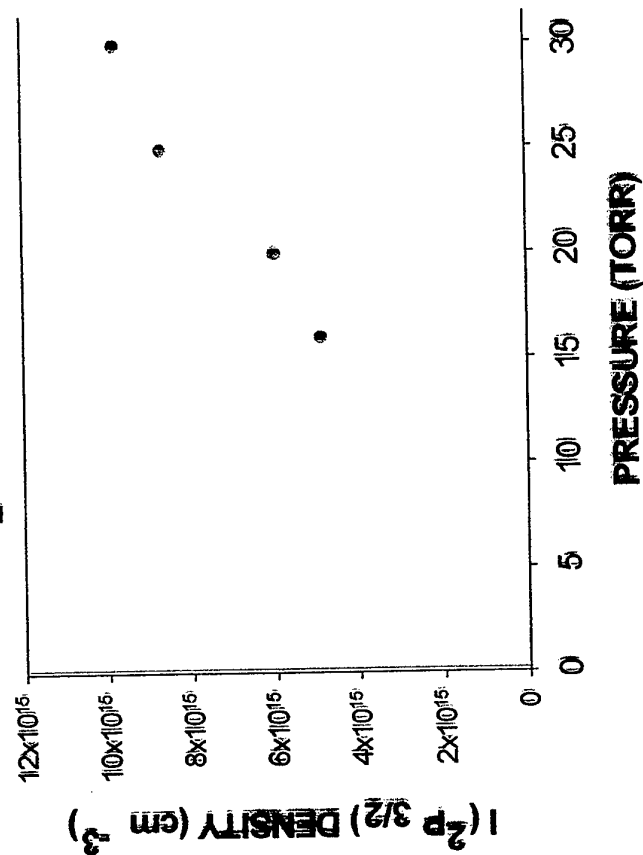


# F ATOM DENSITY SCALING WITH PRESSURE

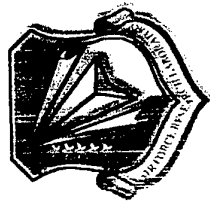
F + H<sub>2</sub> TITRATION, 99043  
 $F_2 = 0.75 \text{ mmol/s}$ ,  $z = 6 \text{ cm}$



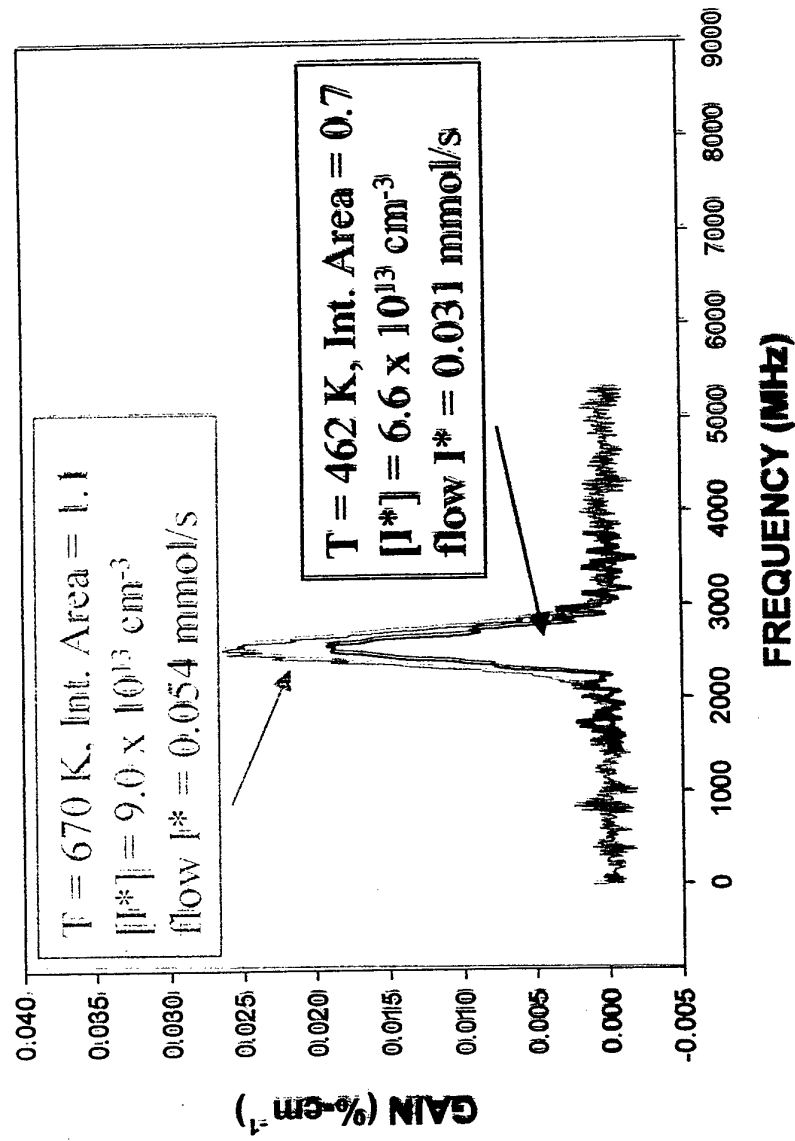
PEAK  $I(2P_{3/2})$  DENSITY vs PRESSURE  
 $F_2 = 0.75 \text{ mmol/s}$ ,  $z = 6 \text{ cm}$







# Recent Small Signal Gain (SSG) Scaling: Approx. 2-Fold Improvement in Gain



9070N: F<sub>2</sub> = 0.75 mmol/s, DCI = 2.0 mmol/s, HI = 0.04 mmol/s, HN<sub>3</sub> = 3.0 mmol/s

P = 19 TORR, z = 7 cm, NORTHSTAR PS

8176Q: F<sub>2</sub> = 0.66 mmol/s, DCI = 2.0 mmol/s, HI = 0.04 mmol/s, HN<sub>3</sub> = 3.0 mmol/s

P = 15 TORR, z = 7 cm, HELIOS PS



## Summary

- **Achieved significant milestone in advanced COIL concept**
- **Demonstrated unambiguous gain in the NCl(a)-I\* system**
- **Current system characterized by low density, limited [F]**
- **Future experiments:**

**scale system to high density, perform laser demonstration**

**Kinetic and thermodynamic aspects of chemical  
generation of atomic iodine for a COIL and their  
consequences for experiments**

Vít Jirásek, Otomar Špalek and Jarmila Kodymová  
Institute of Physics, Prague

## OVERVIEW

1. Introduction into subject
2. Chemical generation of atomic iodine
  - chemical generation of  $I(^2P_{3/2})$  via atomic fluorine
  - chemical generation of  $I(^2P_{3/2})$  via atomic chlorine
3. Modelling of the reaction system
  - system with atomic fluorine
  - system with atomic chlorine
4. Summary

## 1. Introduction into subject

COIL operation - strongly influenced by a ratio  $[I_2]/[O_2(^1\Delta_g)]$

**Disadvantage** of use of molecular iodine :

- difficult supply, both from solid and liquid phase
- meaningful part of stored energy in  $O_2(^1\Delta_g)$  is consumed for  $I_2$  dissociation

→ use of atomic iodine : an estimated **increase up to 25% in laser power**

Possible techniques for an **atomic iodine production** :

- discharge techniques ( dc discharge of alkyl iodides<sup>1</sup>, microwave discharge technique<sup>2</sup>)
- chemical reaction (used for  $NCl(a^1\Delta) + I$  laser<sup>3</sup>)

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<sup>1</sup> N.P. Vagin, N.N. Yuryshev, *Proc. SPIE* Vol. **3574**, 321 (1998)

<sup>2</sup> M. Endo, M. Kawakami, S. Takeda, F. Wani, T. Fujioka, *Proc. SPIE* Vol. **3612**, 56 (1999)

<sup>3</sup> T.L. Hanshaw, T.J. Madden, J.M. Herbelin, G. C. Manke, B.T. Anderson, R.T. Tate, G.D. Hager, *Proc. SPIE* Vol. **3612**, 147 (1999)

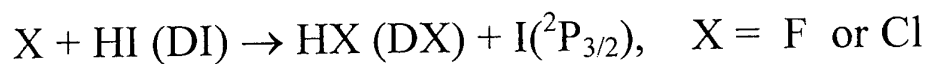
## 2. Chemical generation of atomic iodine

### Aims:

- purely chemical generation
- method suitable for a cw COIL operation
- use of commercially available gases

### Suggested process :

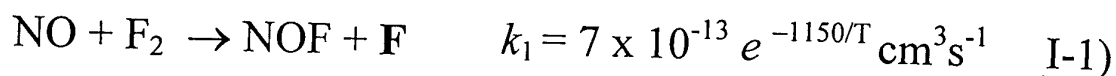
1. production of F or Cl atoms
2. reaction of these atoms with HI :



## Chemical generation of $I(^2P_{3/2})$ via atomic fluorine

### First step : generation of fluorine atoms

$\Rightarrow$  proposed reaction : <sup>4</sup>



$\Rightarrow$  fast

$\Rightarrow$  exothermic ( $-\Delta H^0_{298} = 77 \text{ kJ/mole}$ )<sup>5</sup>

loss processes <sup>6,7</sup>:



<sup>4</sup> C.E. Kolb, *J. Chem. Phys.* **64**, 3087 (1976)

<sup>5</sup> S. Johnston, H. J. Bertin, *J. Amer. Chem. Soc.* **81**, 6402 (1959)

<sup>6</sup> F.G. Skolnik, S.W. Veysey, M.G. Ahmed, W.E. Jones, *Can. J. Chem.* **53**, 3188 (1975)

<sup>7</sup> C.A. Helms, L. Hanco, K. Healey, G. Hager, G.P. Perram, *J. Appl. Phys.* **66**, 6093 (1989)

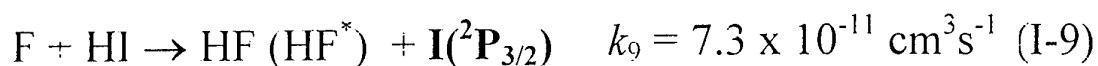
**by-product:** NOF formed partly as  $\text{NOF}^* \rightarrow \text{decays}^6$  :



### **F production efficiency :**

- critically depended on the dilution<sup>7</sup> and  $[\text{F}_2]:[\text{NO}]$  ratio
- 18 % predicted<sup>8</sup>
- 20-30 % measured<sup>7</sup>

### **Second step : reaction of fluorine atoms with HI**



$\Rightarrow$  **very exothermic** ( $\Delta H_{298}^\circ = -216.7 \text{ kJ/mole}$ ), 75%

transformed to vibrational energy of  $\text{HF}^*$  ( $v \leq 6$ )<sup>9</sup>

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<sup>7</sup> C.A. Helms, L. Hanco, K. Healey, G. Hager, G.P. Perram, *J. Appl. Phys.* **66**, 6093 (1989)

<sup>8</sup> J.M. Hoell, F. Allario, O. Jarrett, R.K. Seals, *J. Chem. Phys.* **38**, 2896 (1973)



also electronically excited iodine atoms  $I^*(^2P_{1/2})$  may be formed <sup>10</sup>:



$\Rightarrow$  insufficient for a laser action due to the actual branching ratio of  $I^*(^2P_{1/2})$

HI molecule - **inefficient quencher of  $O_2(^1\Delta_g)$** <sup>11</sup>:



quenching of  $I^*$  :



$\Rightarrow$  important for COIL operation

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<sup>9</sup> N. Jonathan, C.M. Melliar-Smith, S. Okuda, D.F. Slater, D. Timlin, *Molecular Physics* **22**, 561 (1971)

<sup>10</sup> U. Dinur, R. Kosloff, R.D. Levine, *Chem. Phys. Lett.* **34**, 199 (1975)

<sup>11</sup> J.B. Koffend, C.E. Gardner, R.F. Heidner, *J. Chem. Phys.* **80**, 1861 (1984)

## Chemical generation of $I(^2P_{3/2})$ via atomic chlorine

### First step : generation of chlorine atoms

overall process<sup>12</sup> :



chain-branching reaction scheme<sup>12,13</sup>:

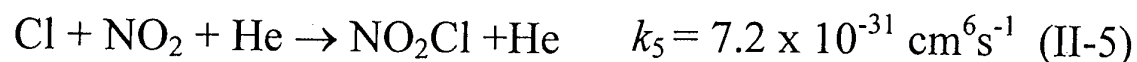


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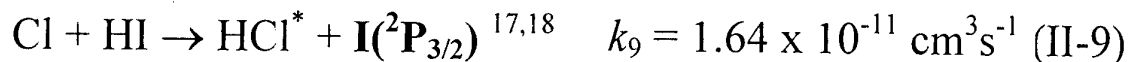
<sup>12</sup> S.J. Arnold, K.D. Foster, D.R. Snelling, R.D. Suart, *Appl. Phys. Lett.* 30, 637 (1977)

<sup>13</sup> S.J. Arnold, K.D. Foster, D.R. Snelling, R.D. Suart, *IEEE J. Quant. Electr.* QE-14, 293 (1978)

loss processes :



### Second step : reaction of chlorine atoms with HI

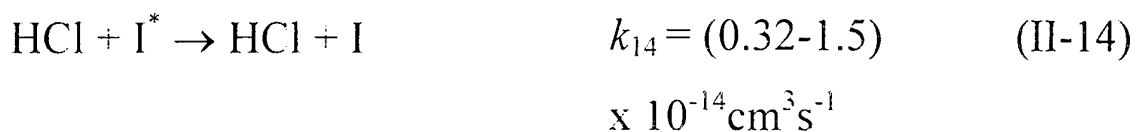
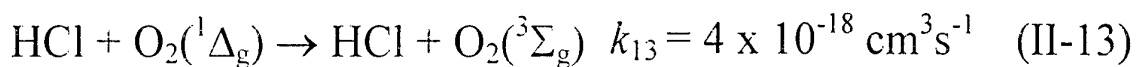
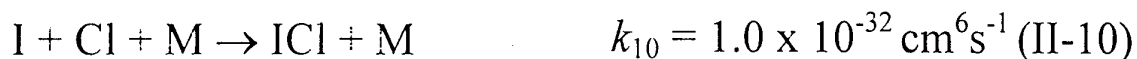


$\Rightarrow 132.5 \text{ kJ/mole}$  exothermic<sup>9</sup>, 70% transformed to vibrational energy in  $\text{HCl}^*$ <sup>14</sup>

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<sup>14</sup> J.C. Polanyi, K.B. Woodall, *J.Chem.Phys.* 56, 1563 (1972)

side reactions<sup>13,15,16</sup> :



**method successfully applied in operating purely chemical  
HCl and HCl/CO<sub>2</sub> transfer lasers<sup>12,13</sup>**

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<sup>15</sup> Kulagin, Yarygina et al<sup>94</sup>

<sup>16</sup> J.P. Singh, J. Bachar, D.W. Setser, S. Rosenwaks, *J. Phys.Chem.* 89, 5347 (1985)

### 3. Modelling of the reaction systems

#### specifications :

- one dimensional model
- reactants introduced directly into the primary flow of COIL
- instantaneous mixing
- heat transfer to the walls neglected
- fluid dynamic neglected
- enthalpy balance with  $c_p \neq c_p(T)$  included

flow and pressure conditions → typical for the subsonic channel of our SCOIL :

Cl <sub>2</sub> flowrate	40 mol/s
pr. He flowrate	80 mmol/s
sec. He flowrate	40 mmol/s
total pressure	4 kPa
O <sub>2</sub> ( <sup>1</sup> Δ <sub>g</sub> ) pressure	580 Pa
flow speed	100 m/s

## **Reaction system with atomic fluorine as intermediate reactant**

### **First step : production of atomic fluorine**

- reactions (I-1) - (I-3) and (I-5) included
- wall recombination neglected
- reactions with primary flow components neglected
- $\Delta H_r$  of reactions (I-1) and (I-3) included

### **Results :**

- 30 % maximum efficiency of F atoms at ratio  
 $[F_2]:[NO]:[He]=1:2:30$
- high temperature ( 550 K )
- 10 cm reaction path for maximum [F]
- high residual concentrations of NO, F<sub>2</sub> and NOF

## Second step : HI added into the system

1. HI injected together with  $F_2+NO+He$  mixture
  2. HI injected downstream to the primary flow at the place of maximum  $[F]$  concentration
- reaction (I-9) and recombination of I atoms (II-11) added
  - quenching processes by HI neglected

### Results :

- 100 % conversion of HI to  $I$
- HI injected together with  $F_2+NO+He$  mixture :
  - long reaction path
  - 90 % conversion at 50 cm
  - temperature 525 K
- HI injected 9.6 cm downstream of  $F_2+NO+He$  mixture :
  - 55 % conversion at 23 cm
  - temperature 800 K

## **Reaction system with atomic chlorine as intermediate reactant**

### **First step : production of atomic chlorine :**

- reactions (II-2) - (II-7) included
- $\Delta H_r$  of reactions (II-2), (II-3) included
- recombination of Cl atoms neglected
- reactions with primary flow components neglected

### **Results :**

- ClO is the main product at ratio  $[\text{ClO}_2]:[\text{NO}]:[\text{He}]=1:1:75$
- 56 % maximum efficiency of Cl atoms at ratio  
 $[\text{ClO}_2]:[\text{NO}]:[\text{He}]=1:2:75$
- temperature 450 K
- short reaction path for maximum [Cl] ( 0.46 cm )
- high concentration of  $\text{NO}_2$



## **Second step : HI added into the system**

1. HI injected together with  $\text{ClO}_2 + \text{NO} + \text{He}$  mixture
2. HI injected downstream to the primary flow at the place of maximum
  - reaction (II-9) and recombination of I atoms (II-11) added
  - quenching processes by HI neglected

## **Results :**

- best results if HI is injected together with  $\text{ClO}_2 + \text{NO} + \text{He}$  mixture
- 80 % I yield at 5 cm, **maximum 90 % yield** at 20 cm
- temperature 480 K

## 4. Summary

- the most efficient production of atomic iodine :
  - $\text{ClO}_2$ , NO and HI injected as reactants into the subsonic channel
  - 90 % conversion of HI to I when HI injected simultaneously
  - 3 cm reaction path when HI injected 0.46 cm downstream
- reaction scheme with **fluorine atoms** :
  - reaction path substantially longer (50cm)
  - lower yields of atomic iodine (~60 %)
  - separate reactor at higher pressure needed

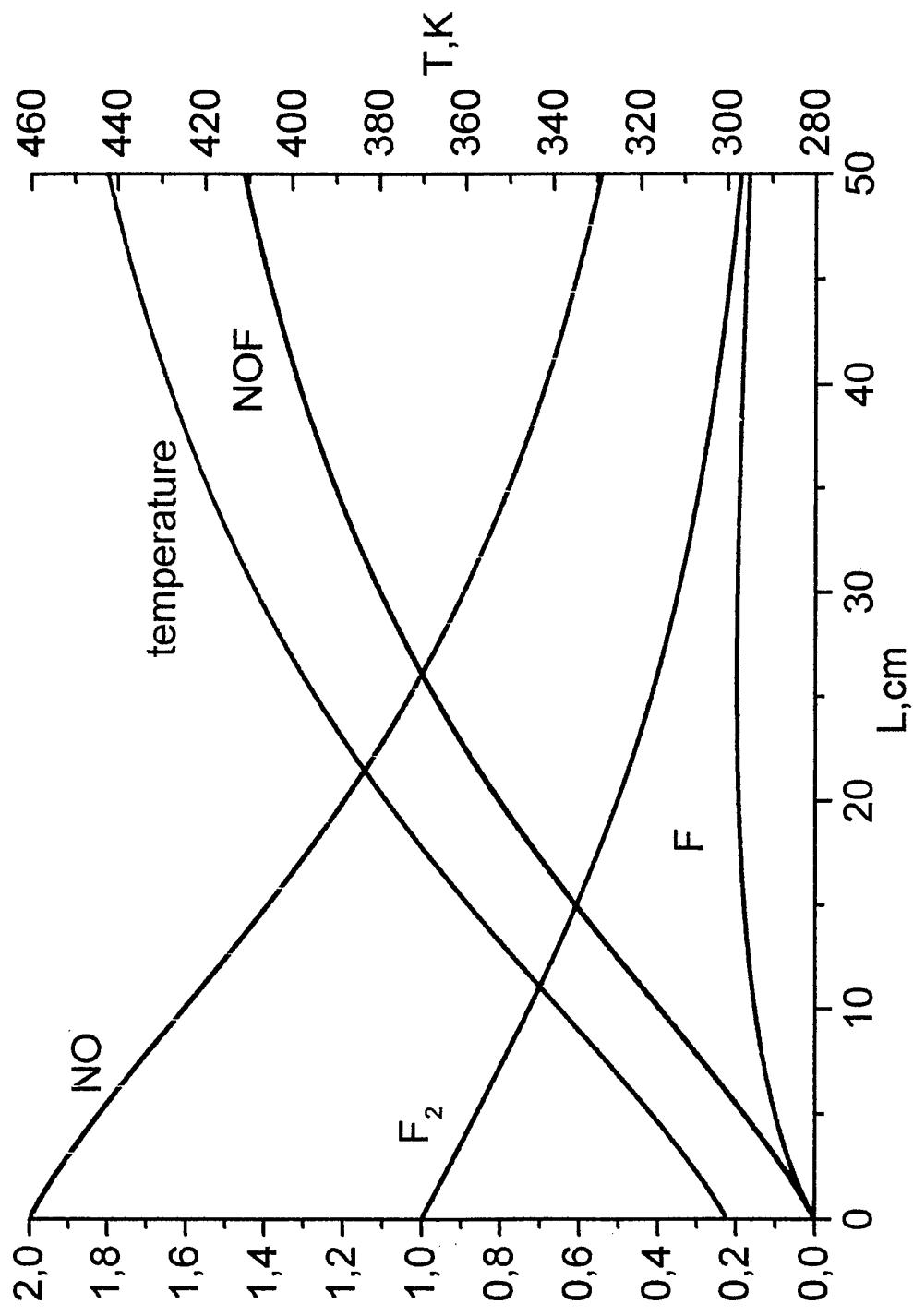


Fig.1a. PRODUCTION OF F ATOMS

Relative concentrations and temperature in reaction system

$$[\text{F}_2] : [\text{NO}] : [\text{He}] = 1 : 2 : 75$$

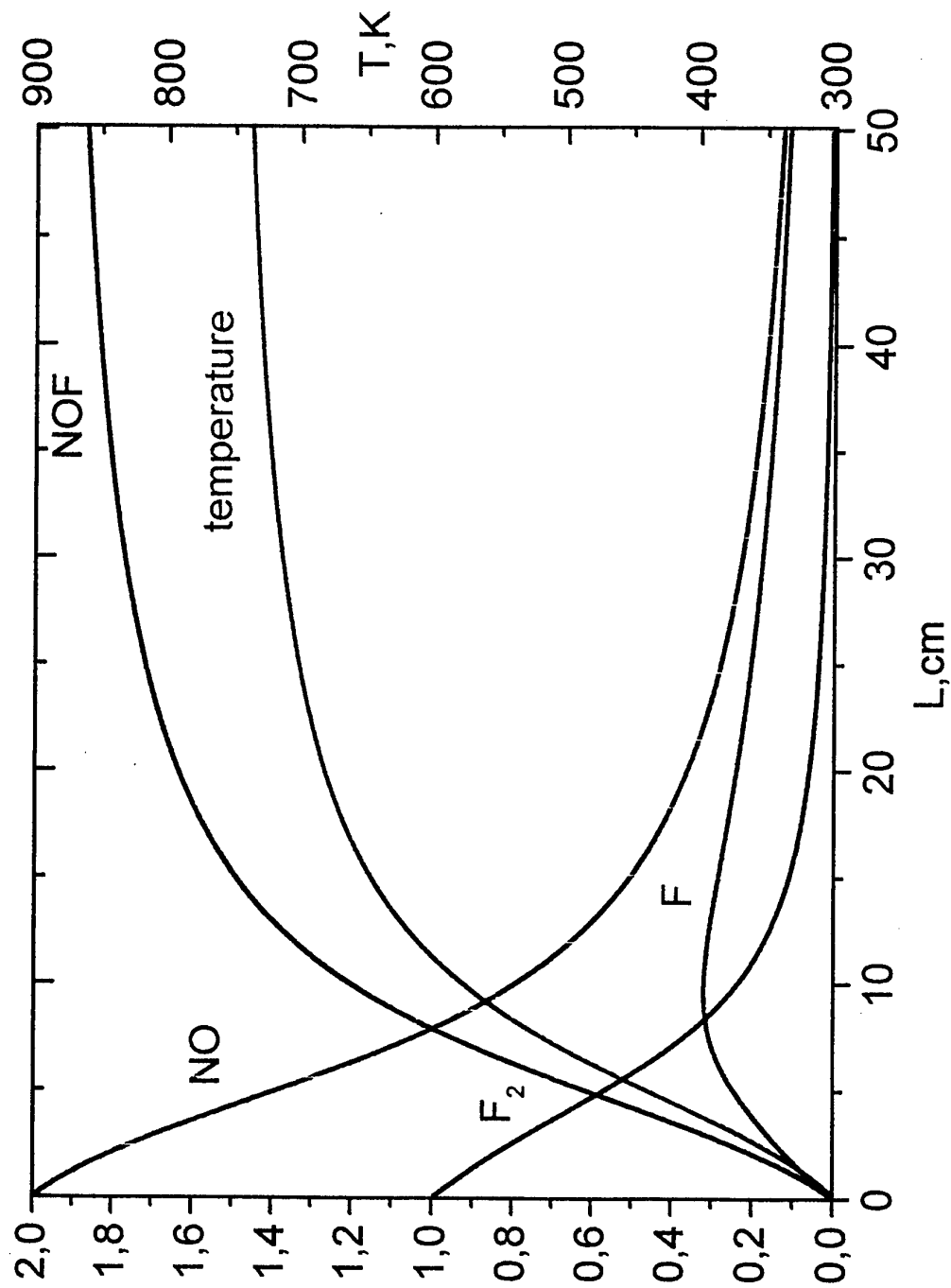


Fig.1b. PRODUCTION OF F ATOMS

Relative concentrations and temperature in reaction system

$$[F_2] : [NO] : [He] = 1 : 2 : 30$$

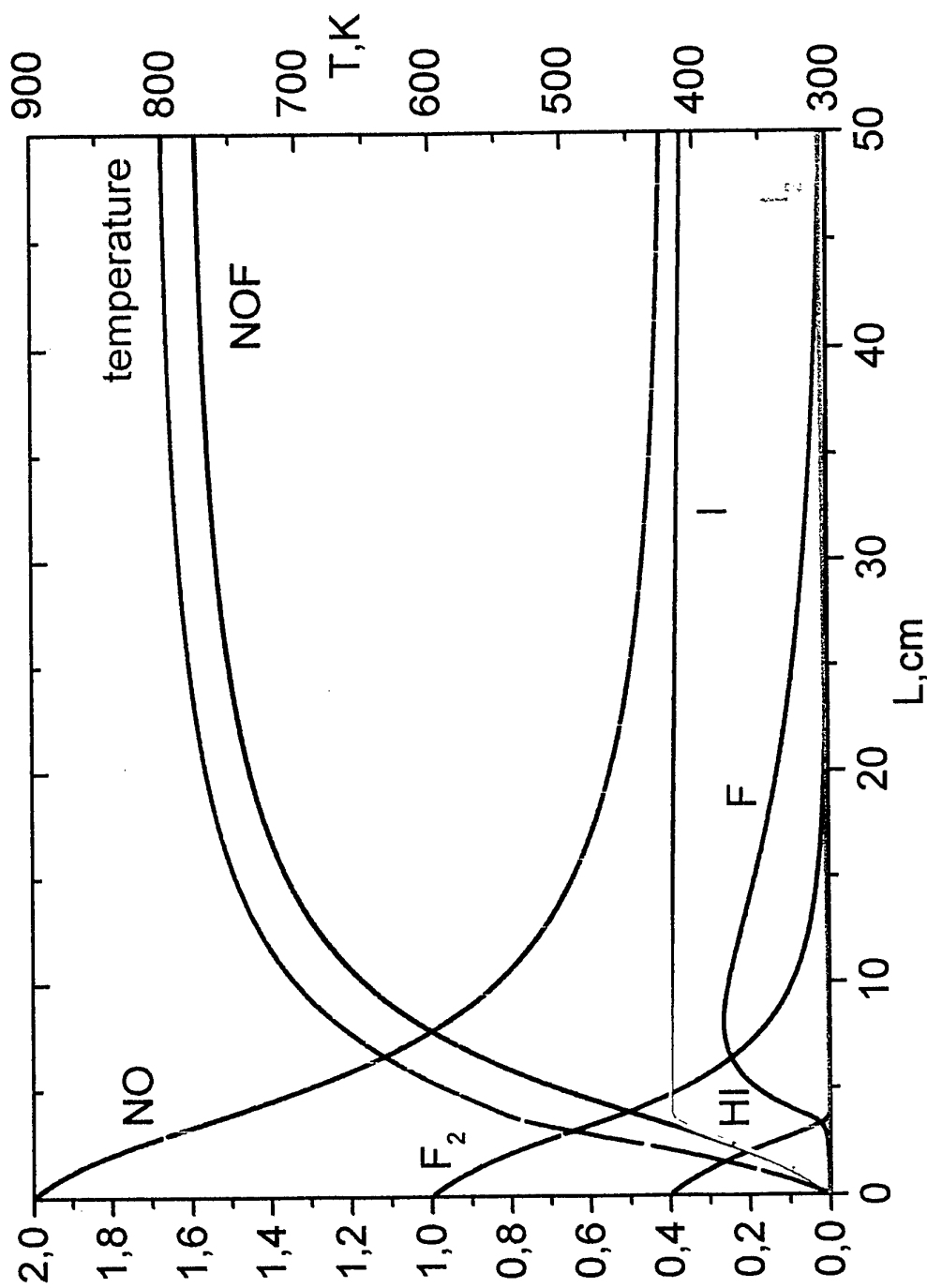


Fig.2. PRODUCTION OF I ATOMS

Relative concentrations and temperature in reaction system

$[F_2] : [NO] : [HI] : [He] = 1 : 2 : 0.4 : 30$

HI injected together with  $F_2 + NO + He$  mixture

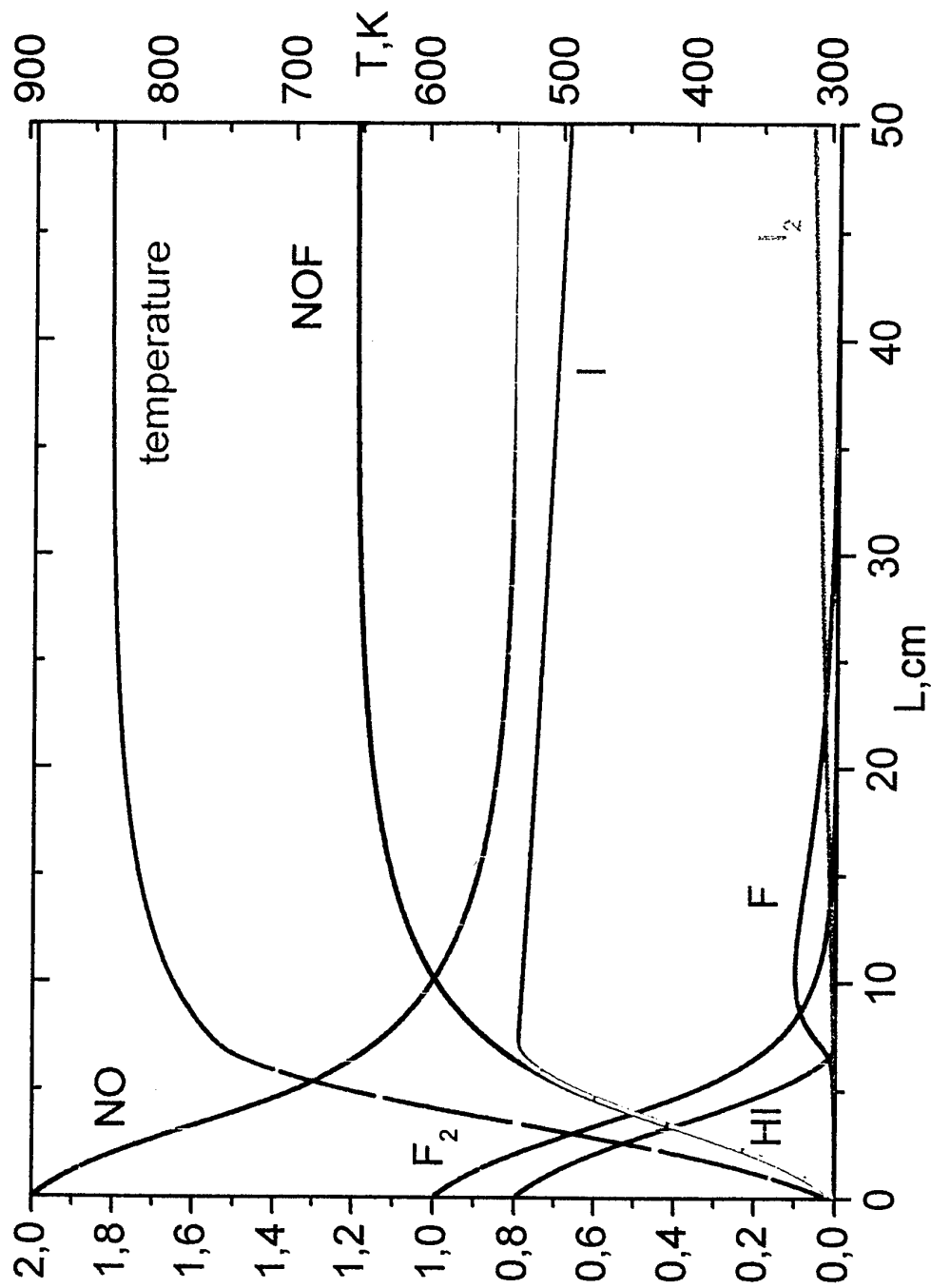


Fig.3. PRODUCTION OF I ATOMS

Relative concentrations and temperature in reaction system

$[F_2] : [NO] : [HI] : [He] = 1 : 2 : 0.8 : 30$

HI injected together with  $F_2 + NO + He$  mixture

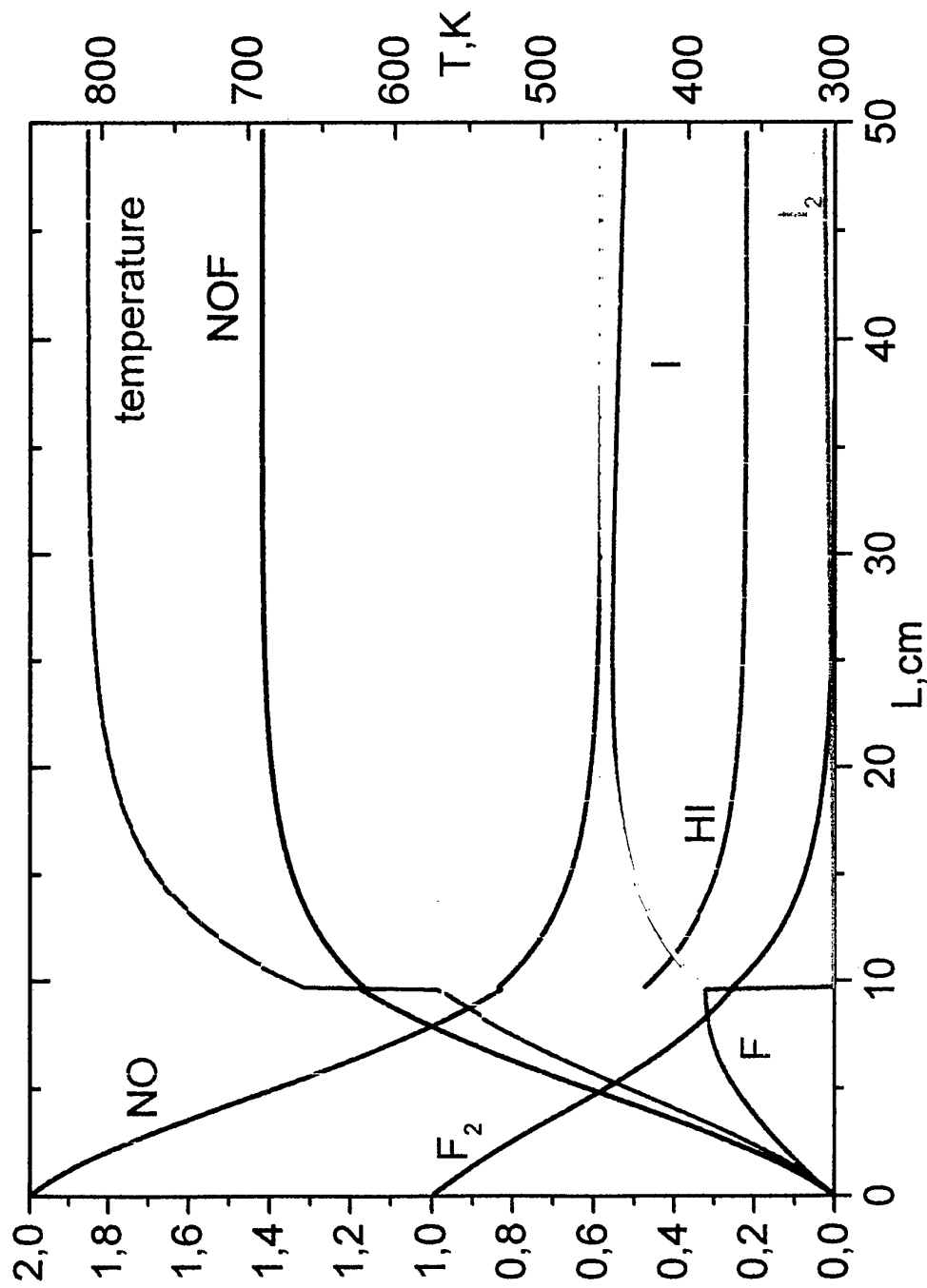


Fig.4. PRODUCTION OF I ATOMS

Relative concentrations and temperature in reaction system

$[F_2] : [NO] : [HI] : [He] = 1 : 2 : 0.8 : 30$

HI injected 9.6 cm downstream of  $F_2 + NO + He$  mixture

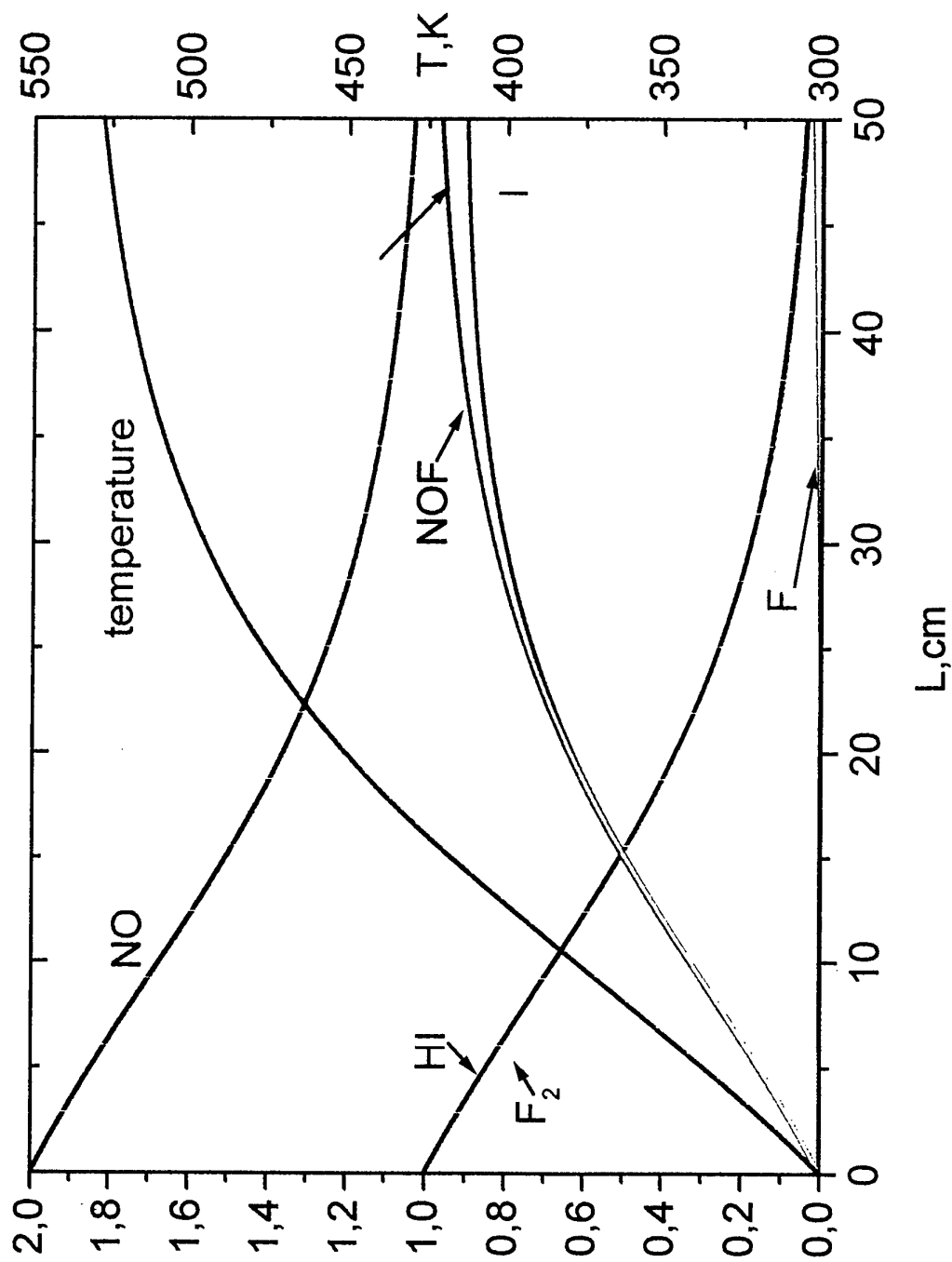


Fig.5. PRODUCTION OF I ATOMS

Relative concentrations and temperature in reaction system

$[F_2] : [NO] : [HI] : [He] = 1 : 2 : 1 : 75$

HI injected together with  $F_2 + NO + He$  mixture



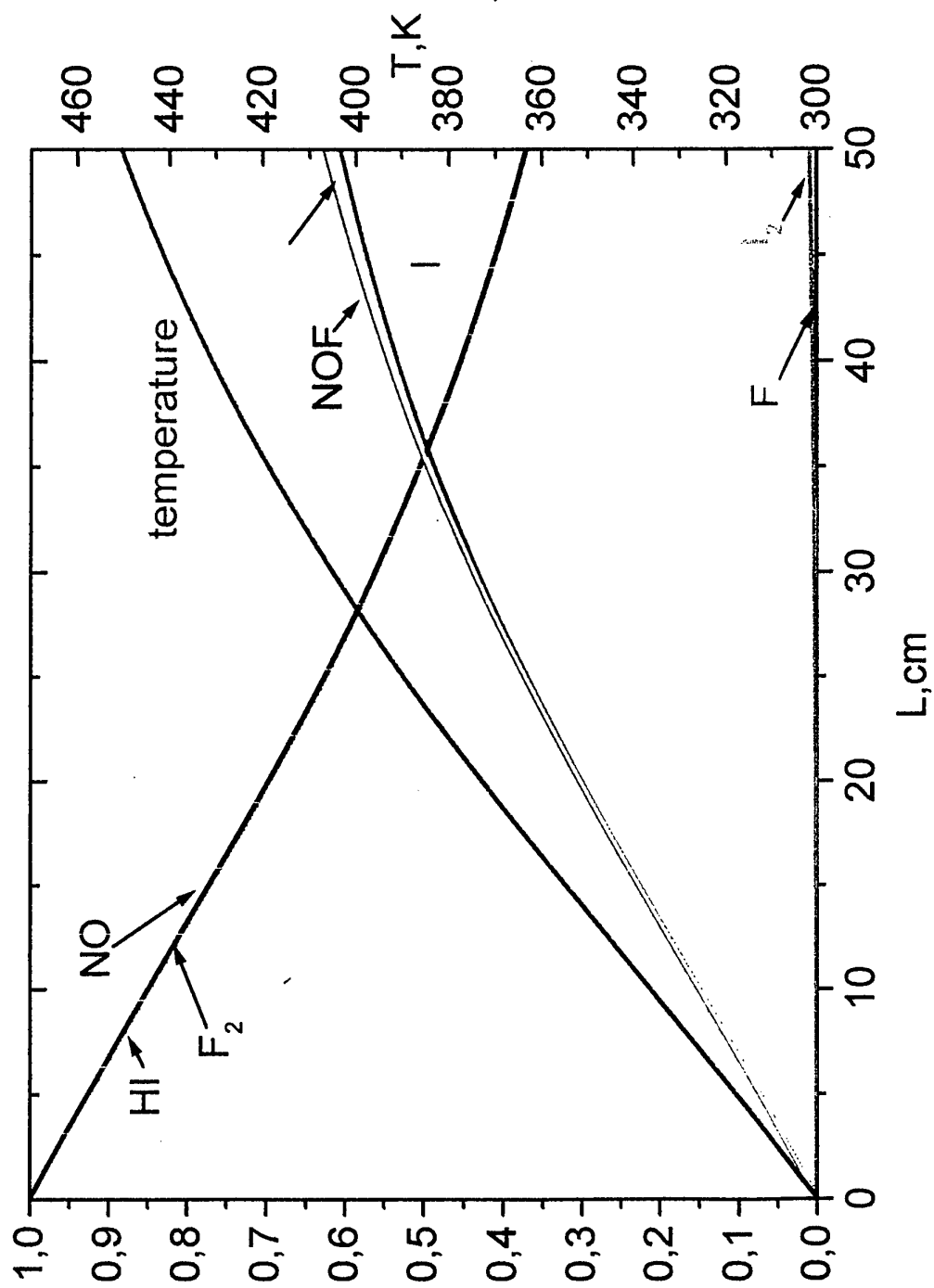


Fig.6. PRODUCTION OF I ATOMS

Relative concentrations and temperature in reaction system

$[F_2] : [NO] : [HI] : [He] = 1 : 1 : 1 : 75$

HI injected together with  $F_2 + NO + He$  mixture

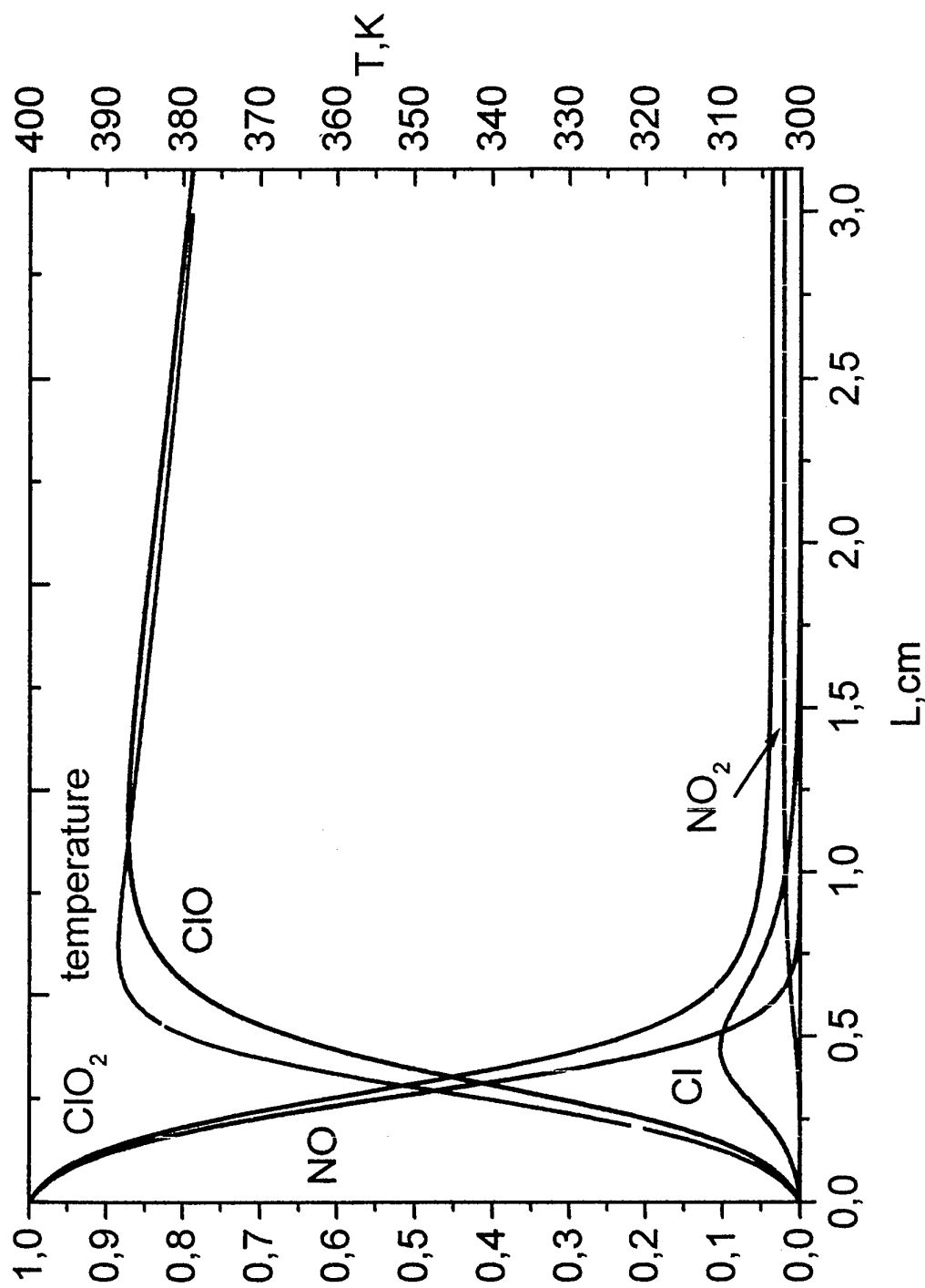


Fig.7 PRODUCTION OF Cl ATOMS

Relative concentrations and temperature in reaction system

$[\text{ClO}_2] : [\text{NO}] : [\text{He}] = 1 : 1 : 75$

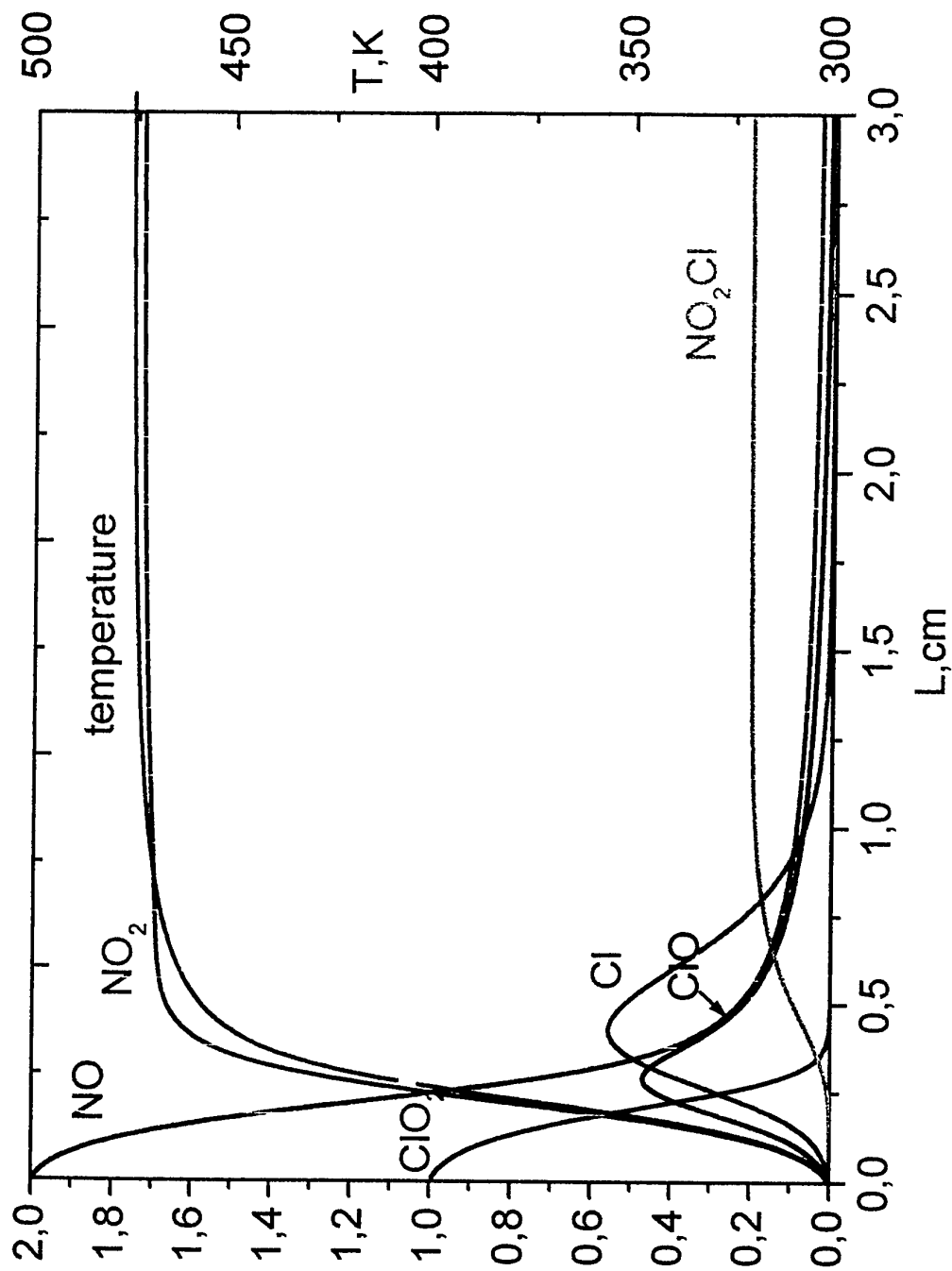


Fig.8 PRODUCTION OF Cl ATOMS

Relative concentrations and temperature in reaction system

$[\text{ClO}_2] : [\text{NO}] : [\text{He}] = 1 : 2 : 75$

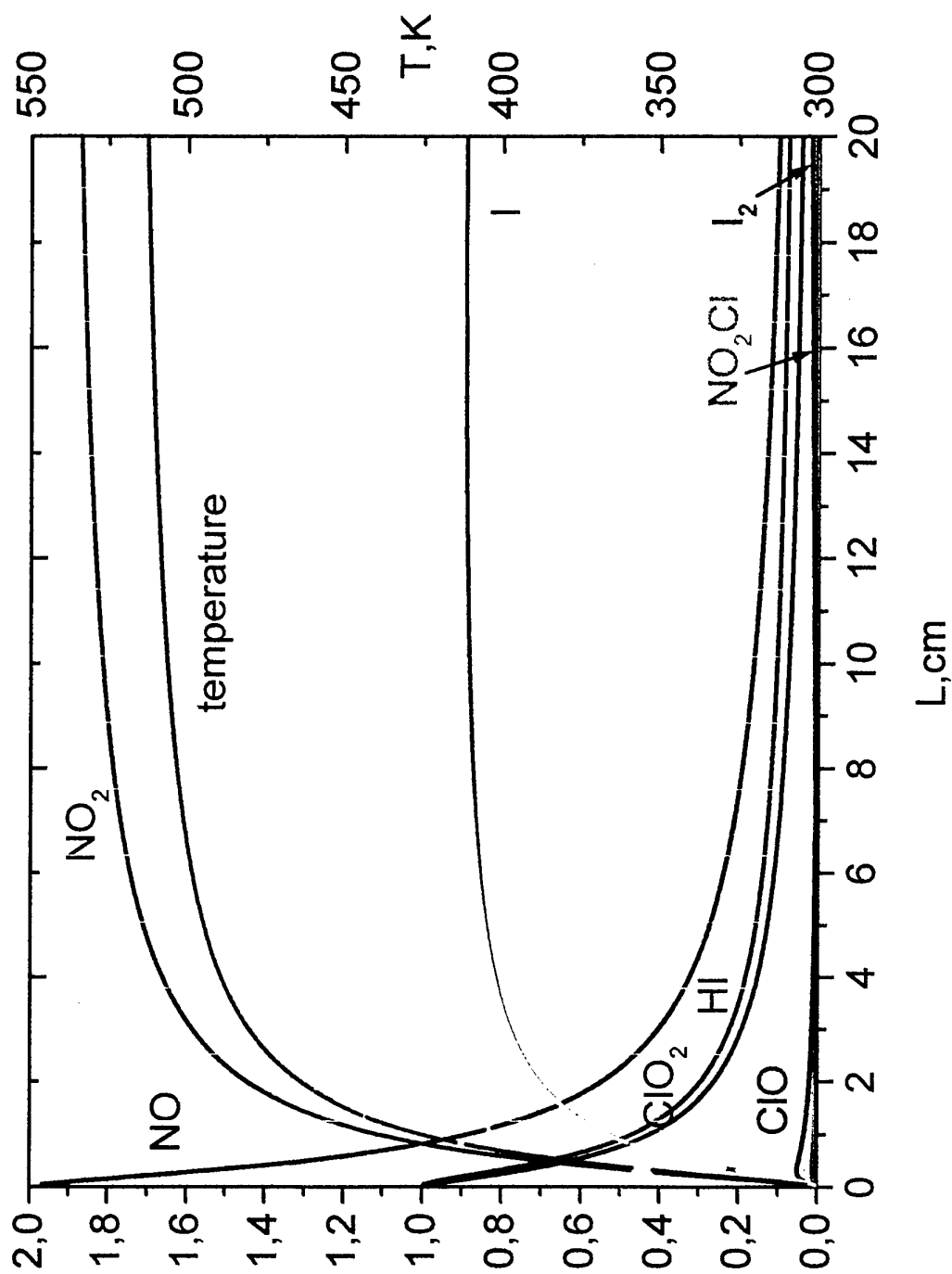


Fig.9 PRODUCTION OF I ATOMS

Relative concentrations and temperature in reaction system

$[\text{ClO}_2] : [\text{NO}] : [\text{HI}] : [\text{He}] = 1 : 2 : 1 : 75$

HI injected together with  $\text{ClO}_2 + \text{NO} + \text{He}$  mixture

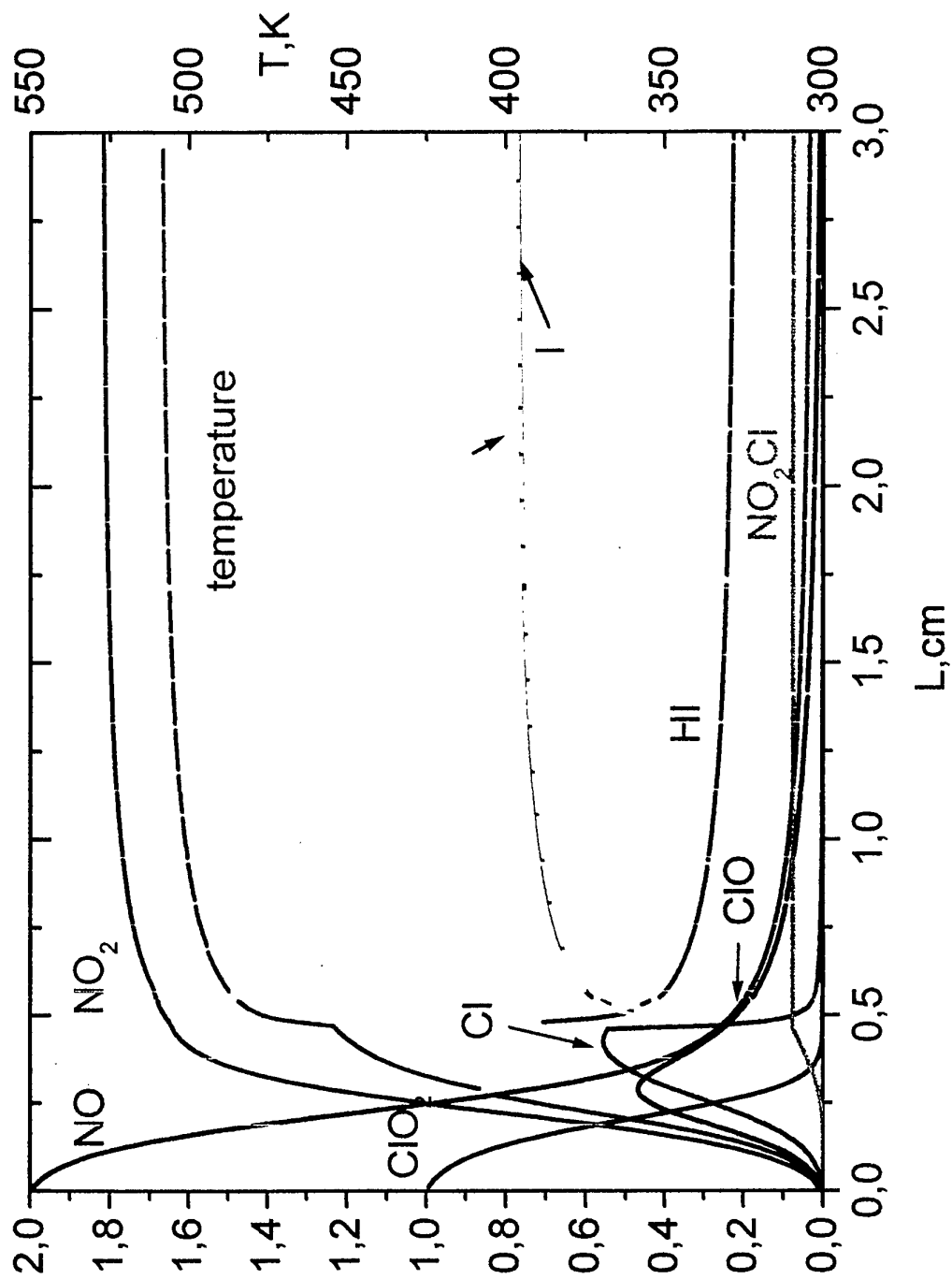


Fig.10 PRODUCTION OF I ATOMS

Relative concentrations and temperature in reaction system

$[\text{ClO}_2] : [\text{NO}] : [\text{HI}] : [\text{He}] = 1 : 2 : 1 : 75$

HI injected 0.46 cm downstream of with  $\text{ClO}_2 + \text{NO} + \text{He}$  mixture

# **PULSED CHEMICAL OXYGEN-IODINE LASER WITH VOLUME GENERATION OF IODINE ATOMS.**

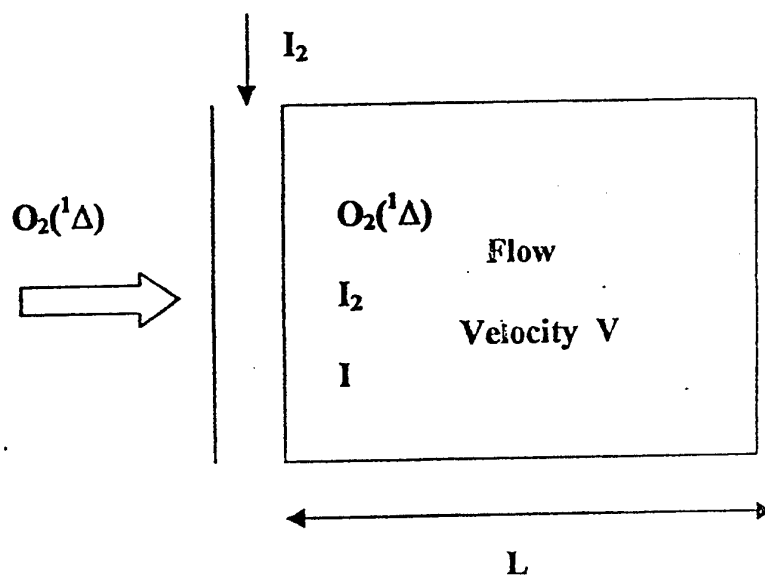
**Yuryshev N. N.**

**P.N. Lebedev Physics Institute  
117924 Moscow, Leninski prospekt 53, Russia**

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- 1. Introduction.**
- 2. Different ways of pulsed mode realization in COIL.**
- 3. Water vapor influence.**
- 4. Pulsed COIL with photolysis.**
- 5. Pressure dependence of output energy. Ozone photolysis as singlet oxygen source.**
- 6. Iodide influence.**
- 7. Pulsed COIL with electric discharge.**
- 8. Pulsed COIL with AOM.**
- 9. COIL pumped solid-state laser.**
- 10. Pulsed COIL as a simulator for the high-power CW laser.**
- 11. Investigation of plasma in oxygen with high singlet oxygen content.**

## CW COIL with Q-switching



Relaxation process  $O_2(^1\Delta) + I(^2P_{1/2}) \rightarrow O_2(^1\Sigma) + I(^2P_{3/2})$   $K_3 = 1 \cdot 10^{-13} \text{ cm}^3/\text{s}$

$$\tau_{\text{rel } 1} = 1 / K_3 [I(^2P_{1/2})] \approx 1 / K_3 [I]$$

$$L_{\text{max}} = V \cdot \tau_{\text{rel } 1}$$

$$E_{\text{stored}} = h\nu [O_2(^1\Delta)] S V / K_3 [I]$$

$$\tau_{\text{pulse}} = 1 / K_{\text{transfer}} [I]$$

$$P_{\text{pulse}} = h\nu [O_2(^1\Delta)] S V K_{\text{transfer}} / K_3 \quad P_{\text{pulse}} / P_{\text{CW}} = K_{\text{transfer}} / K_3 = 7.7 \cdot 10^2$$

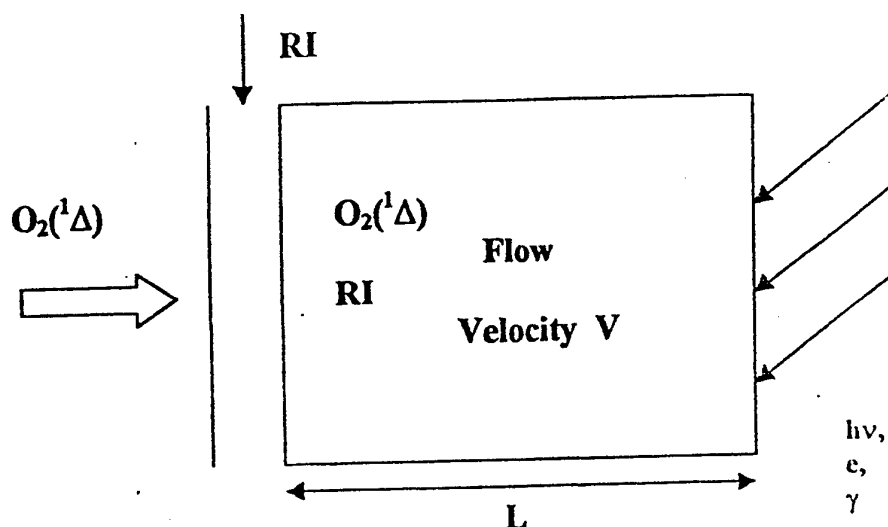
For limited aperture

$$P_{\text{pulse}} / P_{\text{CW}} = L K_{\text{transfer}} [I] / V$$

Experiment

$$P_{\text{pulse}} / P_{\text{CW}} = 16$$

## Pulsed COIL with Volume Generation of Iodine Atoms



Relaxation process  $O_2(^1\Delta) + O_2(^1\Delta) \rightarrow O_2(^1\Sigma) + O_2(^3\Sigma)$   $K_4 = 2 \cdot 10^{-17} \text{ cm}^3/\text{s}$

$$\tau_{\text{rel}2} = 1.7 / K_4 [O_2(^1\Delta)]_0$$

$$L_{\text{max}} = V \cdot \tau_{\text{rel}2}$$

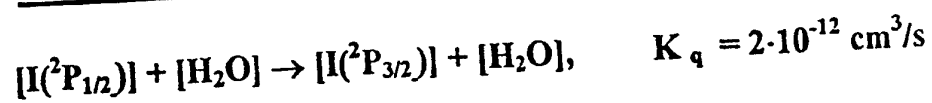
$$\tau_{\text{rel}2} / \tau_{\text{rel}1} = 1.7 K_3 [I] / K_4 [O_2(^1\Delta)]_0 = 8.5 \cdot 10^3 \cdot \{ [I] / [O_2(^1\Delta)] \}$$

$E_{\text{stored}}$  is a function of active medium volume and singlet oxygen pressure.

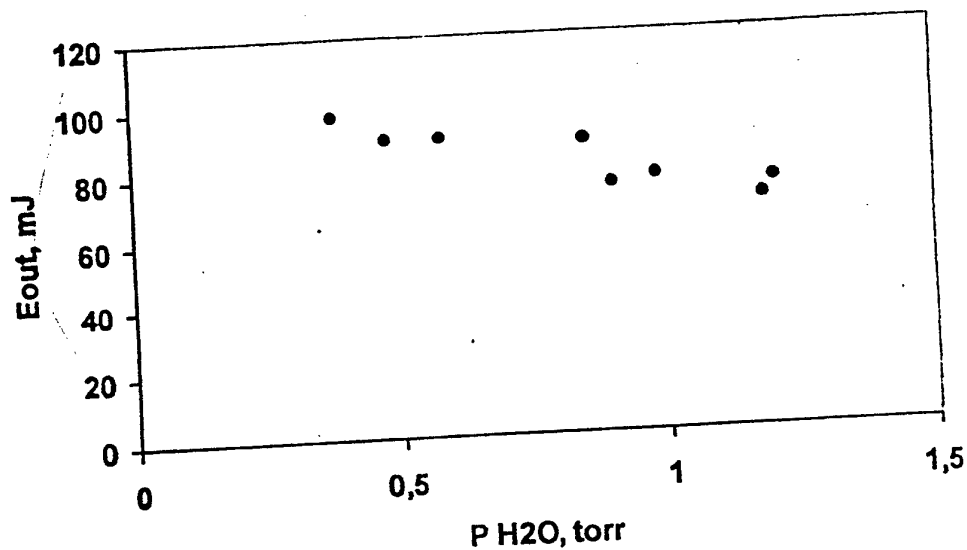
Pulse duration and small signal gain are the functions of iodine atom concentration.



## Influence of Water Vapor Content on Output Energy

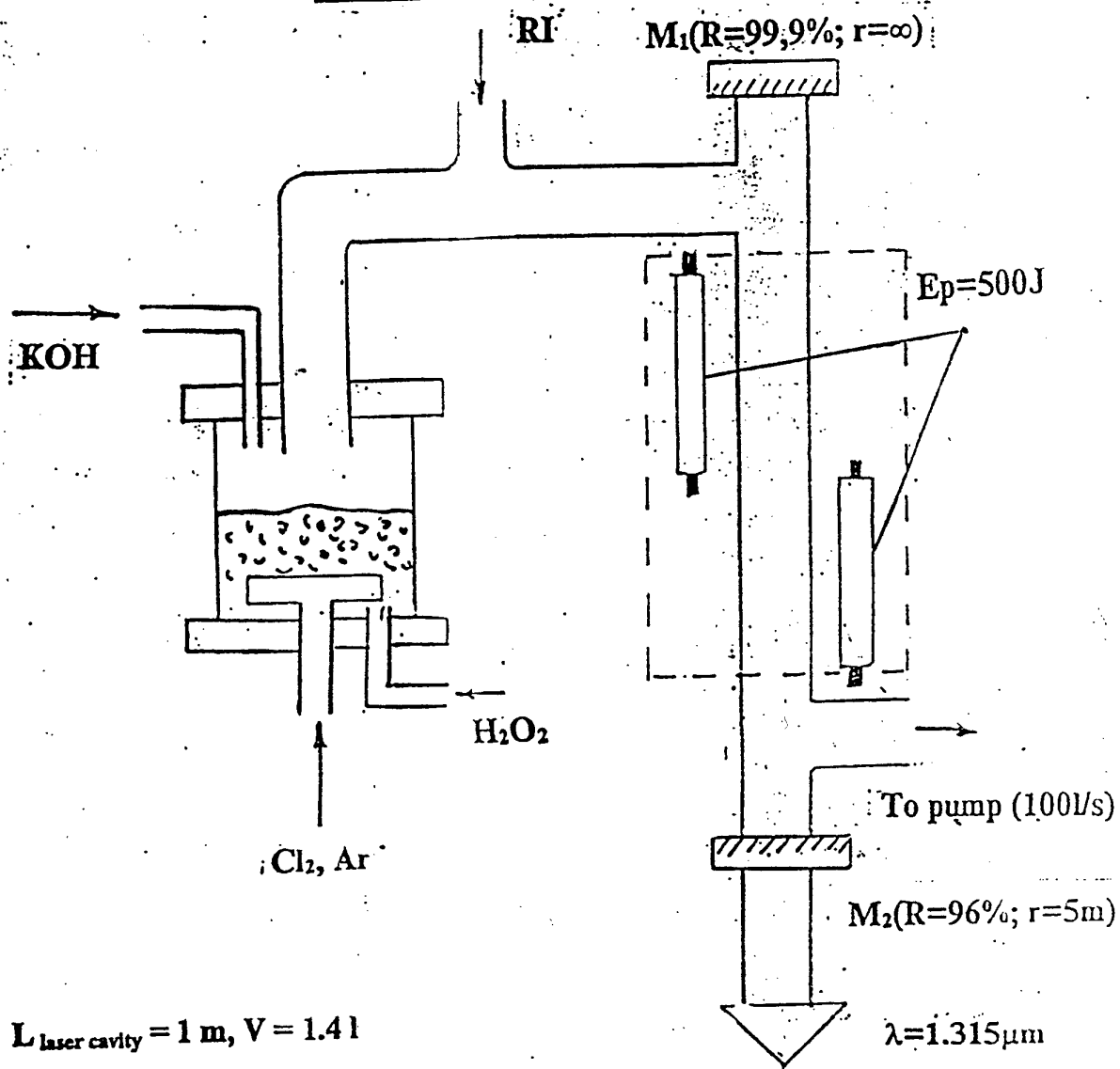


$$K_{\text{transfer}} [O_2(^1\Delta)] [I(^2P_{3/2})] \gg K_q [I(^2P_{1/2})] \cdot [H_2O]$$



Dependence of output energy on the partial pressure of the water vapor,  
 $P_{O_2} = 0.35 \text{ torr}, P_{RI} = 0.12 \text{ torr}$

### Pulsed COIL with photolysis



Iodides investigated:  $\text{CH}_3\text{I}$ ,  $\text{CF}_3\text{I}$ ,  $\text{C}_3\text{F}_7\text{I}$ ,  $\text{C}_3\text{H}_7\text{I}$

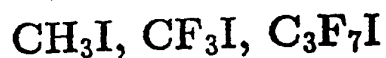
$P_{O_2} = 3$  Torr,       $Cl_2$  flowrate = 20 mmole

$$E_{\text{out}} = 4.4 \text{ J}, \quad \varepsilon_{\text{max}} = 3.1 \text{ J/l}, \quad \tau = 15 - 500 \text{ } \mu\text{s}$$
$$P_{\text{pulse}} = 300 \text{ kW}$$

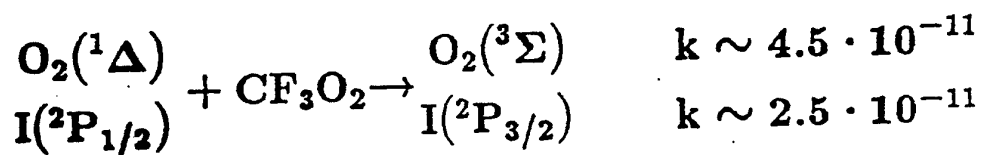
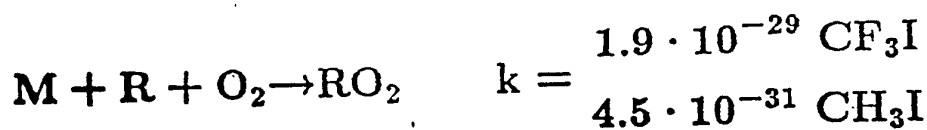
**Intrinsic efficiency = 700 % (depends on iodine concentration produced)**

**Flash lamp efficiency – 10...20%  $\Rightarrow$  Total efficiency – 70...140%**

# IODIDE INFLUENCE

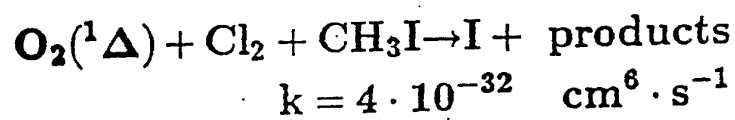


## 1. High $\text{Cl}_2$ utilization

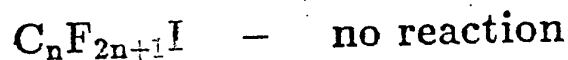


$\text{CH}_3\text{I}$  is preferable

## 2. Deficient $\text{Cl}_2$ utilization

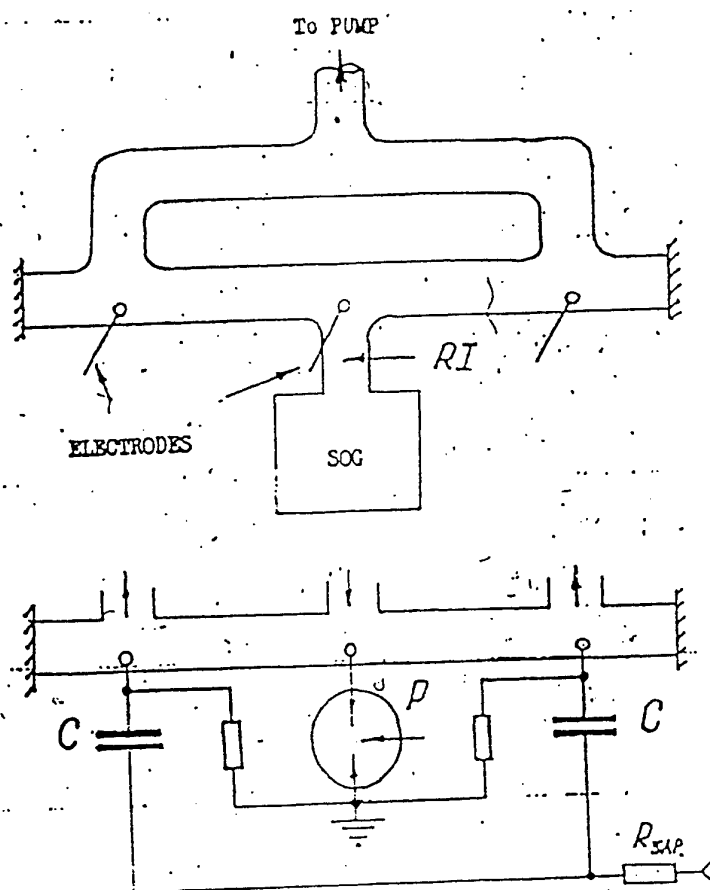


$$k = 4 \cdot 10^{-32} \text{ cm}^6 \cdot \text{s}^{-1}$$



$[\text{Cl}_2]$  control method

## Pulsed COIL with Electric Discharge



Sparger Type Singlet Oxygen Generator

NO WATER VAPOR TRAP

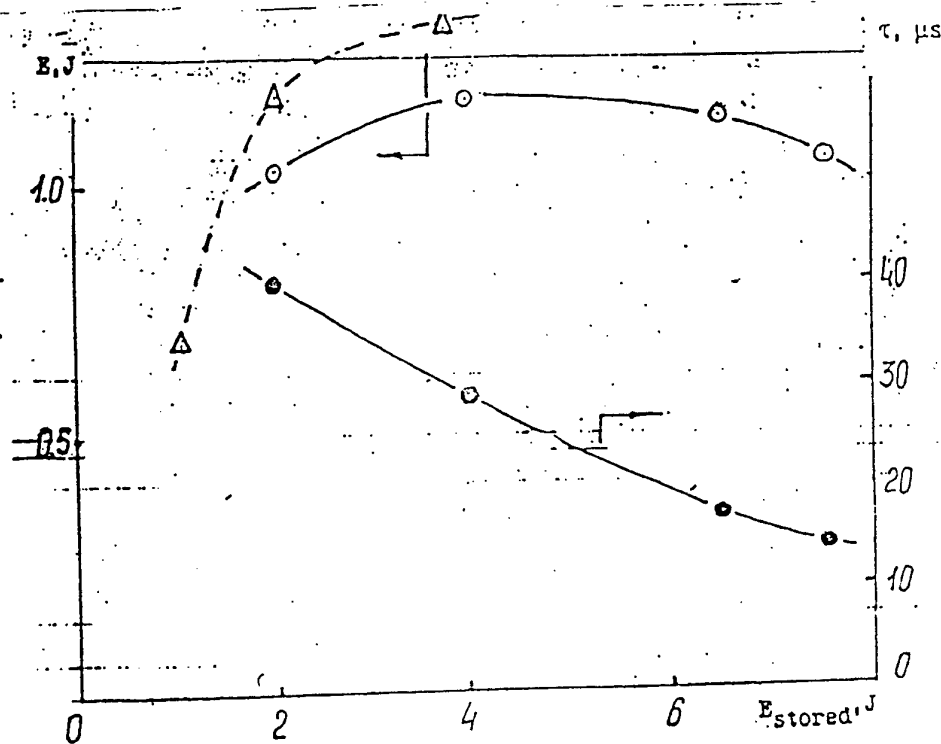
Typical mixture composition:  $O_2$  – to 2 Torr,  $CF_3I$  – to 1 Torr, He(Ar) – to 3 Torr

Chlorine flowrate – 11 mmole / s, Flow velocity – 34 m / s

Discharge parameters:  $U = 14 - 28$  kV / 60 cm,  $\tau = 3$   $\mu$ s  
Capacitor – 5 – 10 nF

Energy stored – 1 – 8 J

## Pulsed COIL with Electric Discharge Experimental results



$21 \text{ eV} \leq \varepsilon_{\text{Iodine atom}} \leq 29 \text{ eV}$ ,      Photolysis:  $\varepsilon_{\text{Iodine atom}} = 5 \text{ eV}$

Buffer gases: He, Ar,  $\text{N}_2$ ,       $E_{\text{He}} : E_{\text{Ar}} : E_{\text{N}_2} = 2 : 1,4 : 1$

$\text{R} = \text{CH}_3\text{I}$ ,  $E_{\text{out}} = 1.8 \text{ J}$ ,      Efficiency = 91%,       $\eta_{\text{chem}} = 10\%$

$P_{\text{pulse}} = 100 \text{ kW}$  at Chlorine flowrate of 14 mmole / s

Repetition operation to 20 Hz

TE facility is under manufacturing

6 7 8 9 10 11 12

11

AE

1000

7

1000

11

## Transfer Flow Transfer Excitation COIL

**Motivation:** ---degradation of output energy of a longitudinal COIL at increased repetition rate

relaxation of energy stored in active medium due to reaction  
 $\text{Cl}_2 + \text{O}_2(^1\Delta) + \text{RI}$

**Background:** --Apollonov and coworkers --simple electrode configuration to drive

HF nonchain laser.  $\text{P}_{\text{SF}_6}$  — 70 Torr, electrode gap — 15 cm

The problem of matching for transverse excitation.

The experimental units designed:

1. 50-cm length laser cell with simple electrode configuration and electrodes treated with sand paper — unsuccessful result  $4 \times 4 \times 50 \text{ cm}^3$   
→ transfer to preionization with surface discharge

2. 5-cm length laser cell with barrier discharge preionization — in progress  $2 \times 2 \times 5$

3. 20-cm length laser cell with resistively loaded pin electrodes — laser generation is obtained.  $E_{\text{out}} = 10 \text{ mJ}$ ,  $\tau_{1/2} = 30 \mu\text{s}$ . Optimization

$\text{O}_2 - 1 \text{ Torr}$ ,  $\text{He} - 3 \text{ Torr}$ ,  $\text{CH}_3\text{I} - 0,5 \text{ Torr}$

$V = 1,5 \times 2 \times 20 = 60 \text{ cm}^3$

$\epsilon = 160 \text{ mJ/l}$   $\eta_{\text{chem}} = 3,3\%$

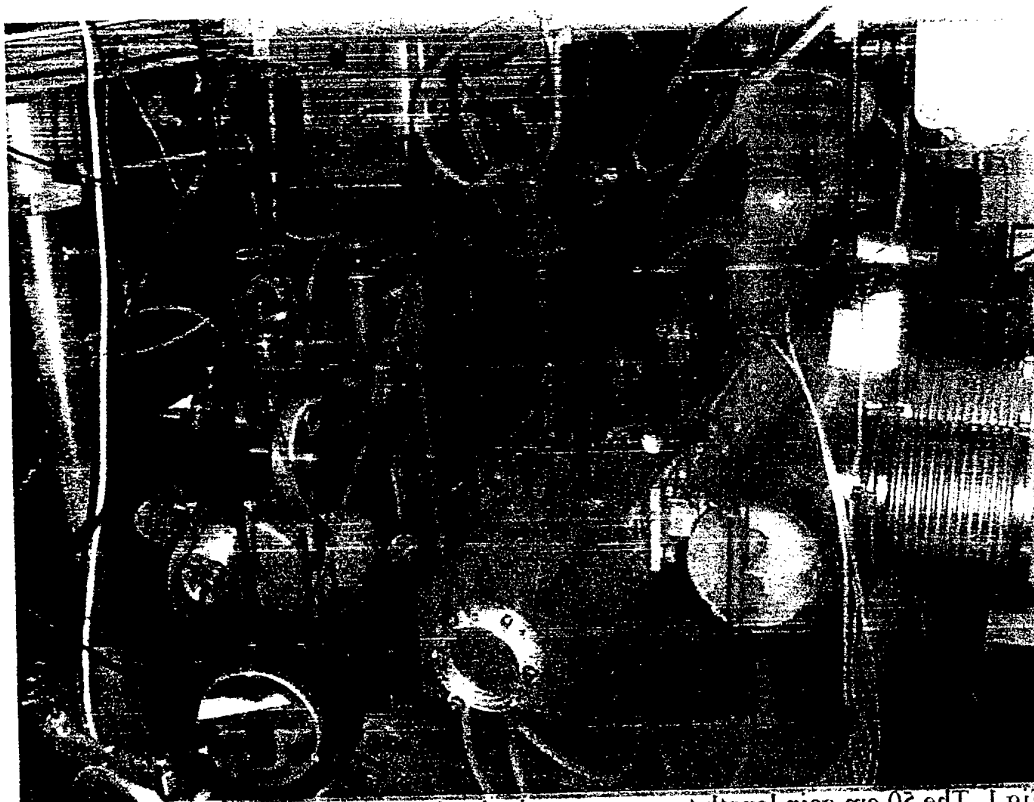


Fig. 1. The 20 cm gain length transverse excitation laser chamber

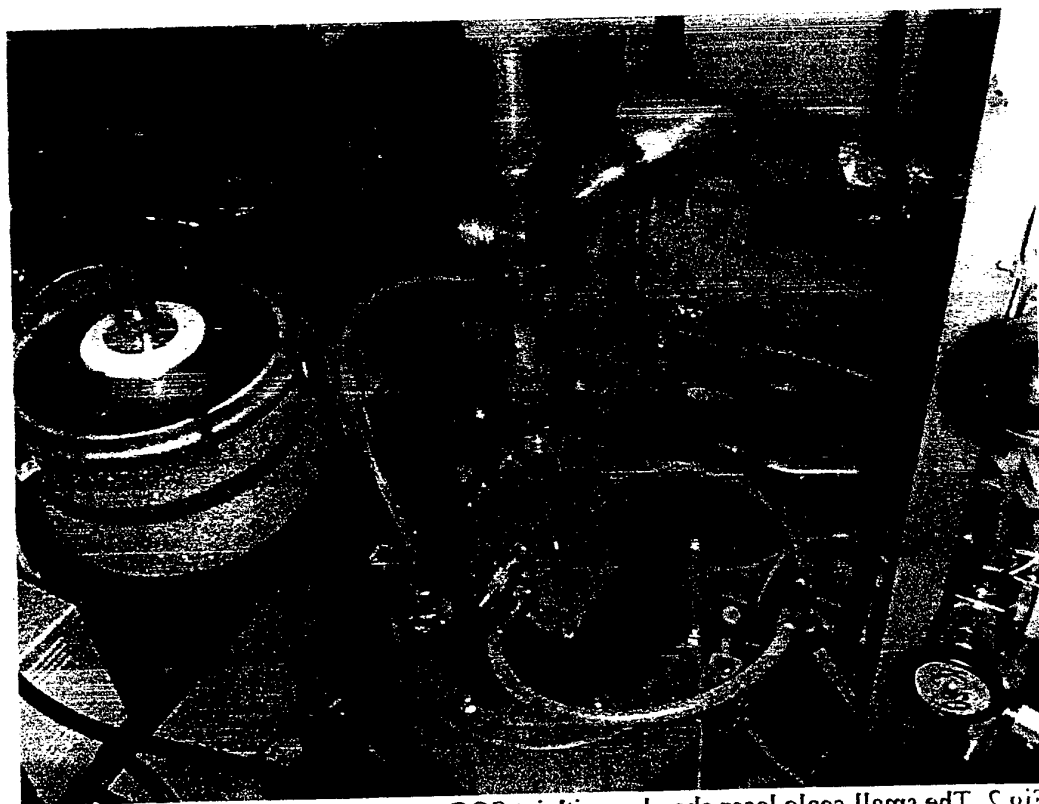


Fig. 2. The small-scale laser chamber with jet SOG



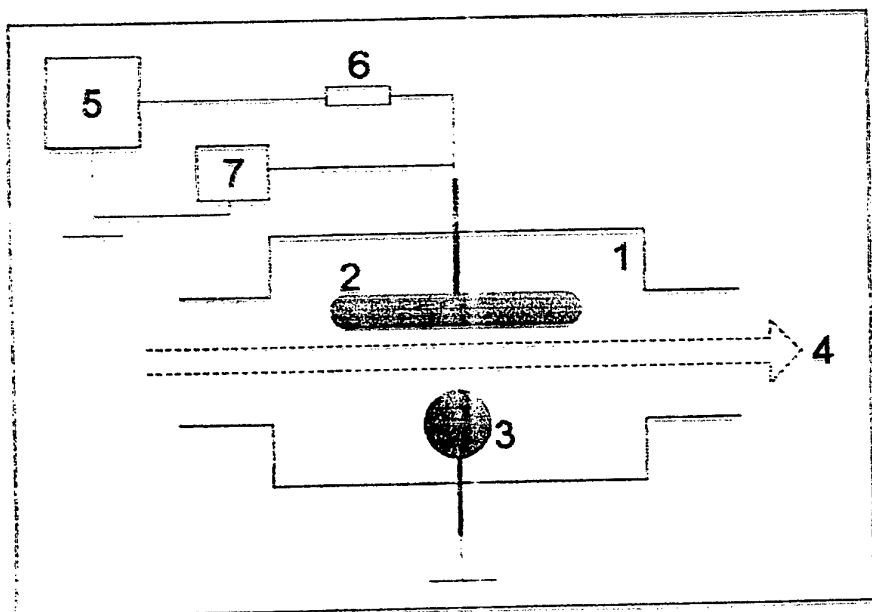
## The break-down parameters of gas oxygen with high SO content

**Motivation:**

- electrical discharge as a source of singlet oxygen
- discharge generation of atomic iodine for COIL

**Expected goal:**

- kinetic information necessary to describe the singlet oxygen behavior in plasma

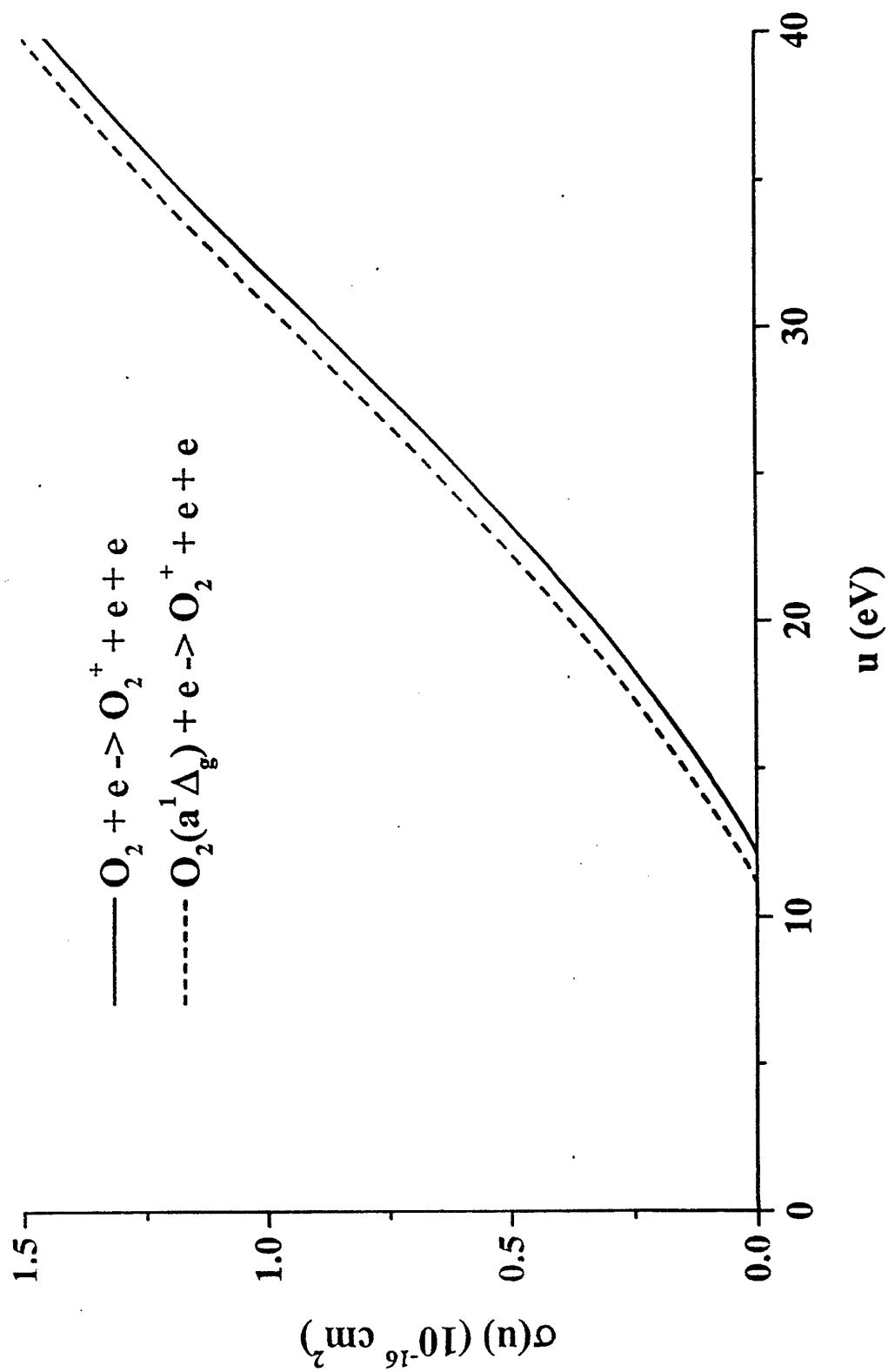


Schematic diagram of experiment: 1-discharge chamber, 2-disk electrode 54.8 mm o.d., 3 negative spherical electrode 20.2 mm o.d., 4-flow direction, 5-regulated high voltage supply, 6-resistor, 7-voltmeter. Electrode gap 6.6 mm

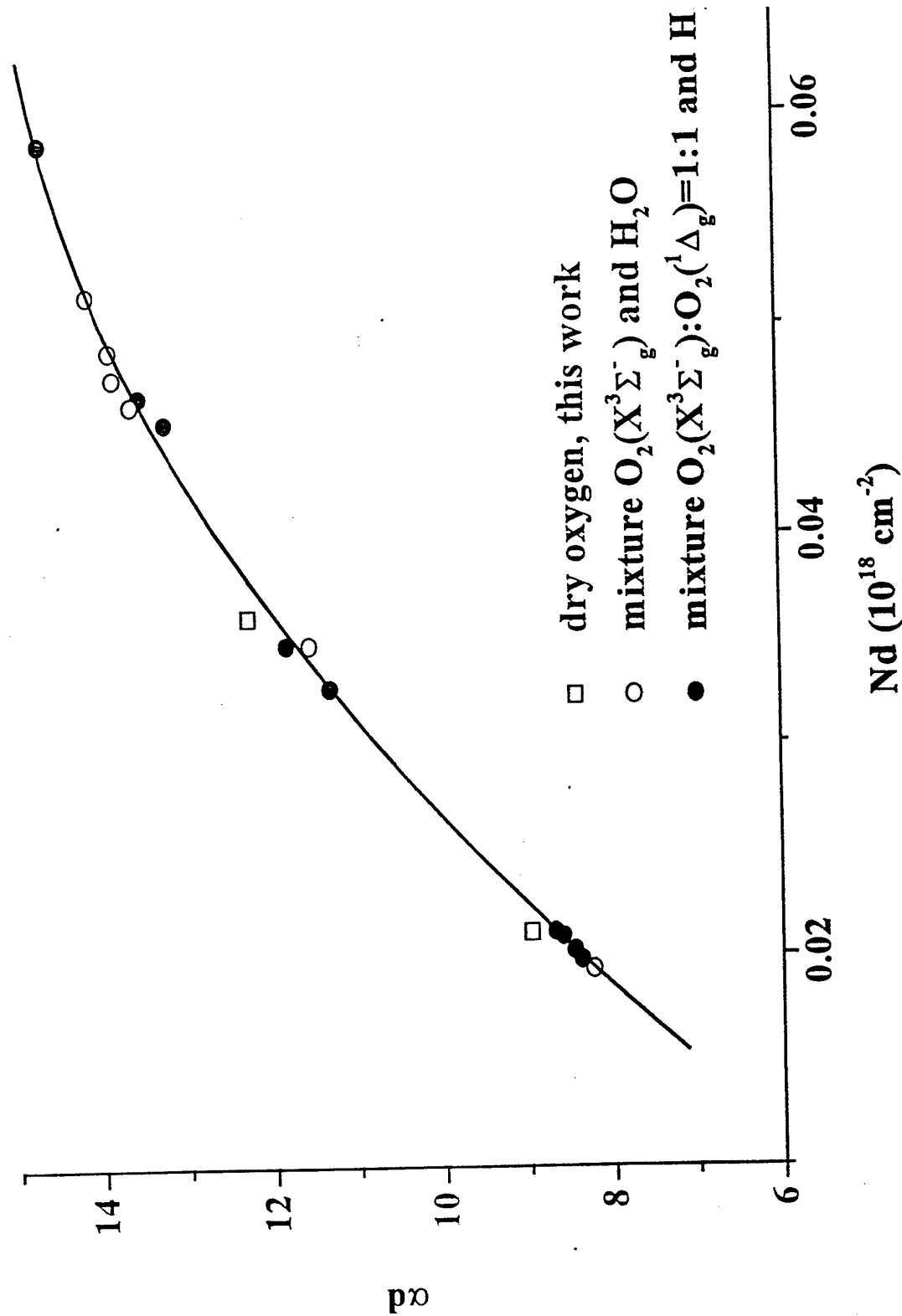
Таблица 1.

№ п/п	O <sub>2</sub> + O <sub>2</sub> ( <sup>1</sup> Δ) (Торр)	O <sub>2</sub> ( <sup>1</sup> Δ)	H <sub>2</sub> O (Торр)	U В	Nd (10 <sup>18</sup> см <sup>-2</sup> )	E/N (10 <sup>-16</sup> Всм <sup>2</sup> )	αd
1	1.4	-	0.1	543	0.0327	166.2	11.31
2	1.4	+	0.1	520	0.0327	159.2	11.32
3	2.1	-	0.15	604	0.0490	123.3	13.86
4	2.0	+	0.15	565	0.0468	120.7	13.52
5	2.1	-	0.09	606	0.0477	127.1	13.82
6	2.0	+	0.09	552	0.0455	121.3	13.22
7	1.4	-	0.2	541	0.0348	155.2	11.56
8	1.4	+	0.2	533	0.0348	152.9	11.83
9	2.1	-	0.03	600	0.0464	129.3	13.62
10	2.1	-	0.27	611	0.0516	118.4	14.12
11	2.0	+	0.7	603	0.0588	102.5	14.66
12	0.88	-	0.01	495.6	0.0194	255.7	8.23
13	0.9	+	0.01	478	0.0198	241.2	8.37
14	0.9	+	0.03	479	0.0203	236.5	8.46
15	0.9	+	0.06	482	0.0209	230.5	8.59
16	0.9	+	0.07	490	0.0211	231.9	8.68
17	0.97	-	-	535.8	0.0211	253.6	12.27
18	1.66	-	-	579.6	0.0362	160.3	8.96

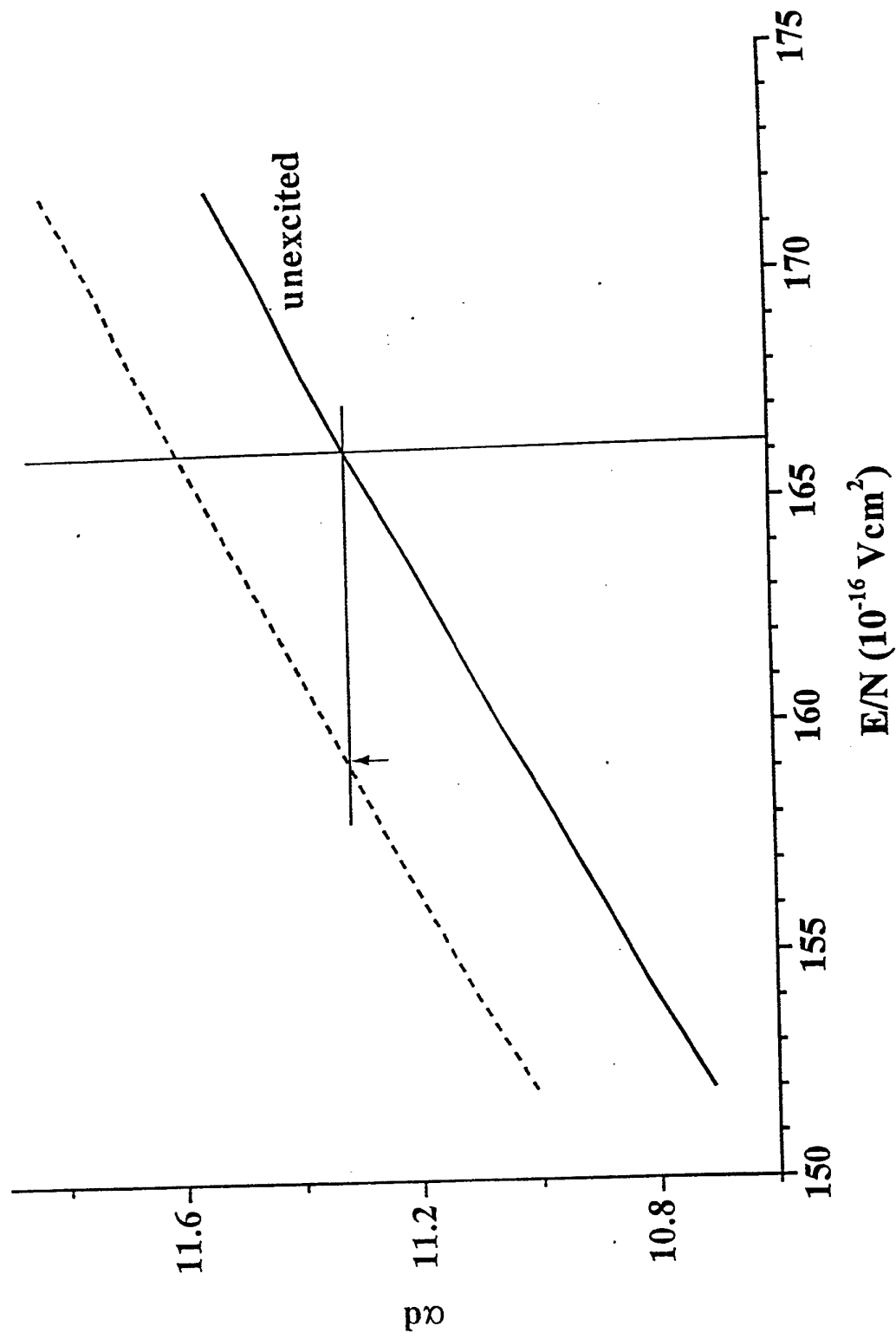
# IONIZATION CROSS SECTION



# IONIZATION COEFFICIENT CALCULATED FOR EXPERIMENTAL MEASURED ELECTRIC FIELD STRENGTHS

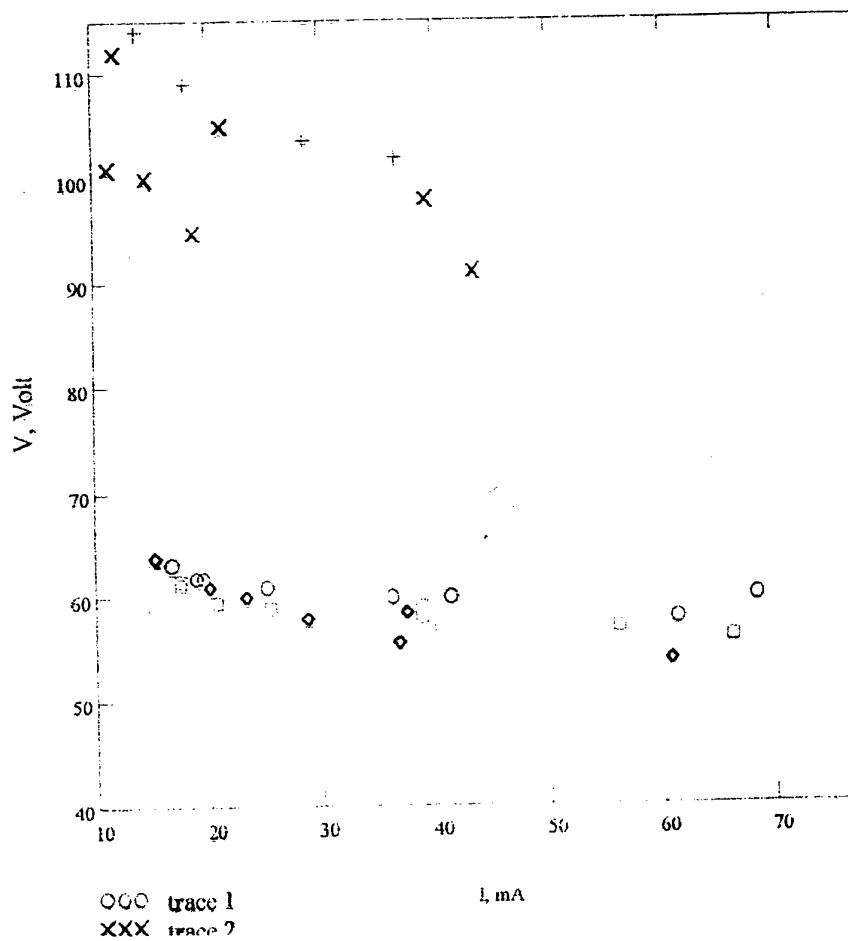
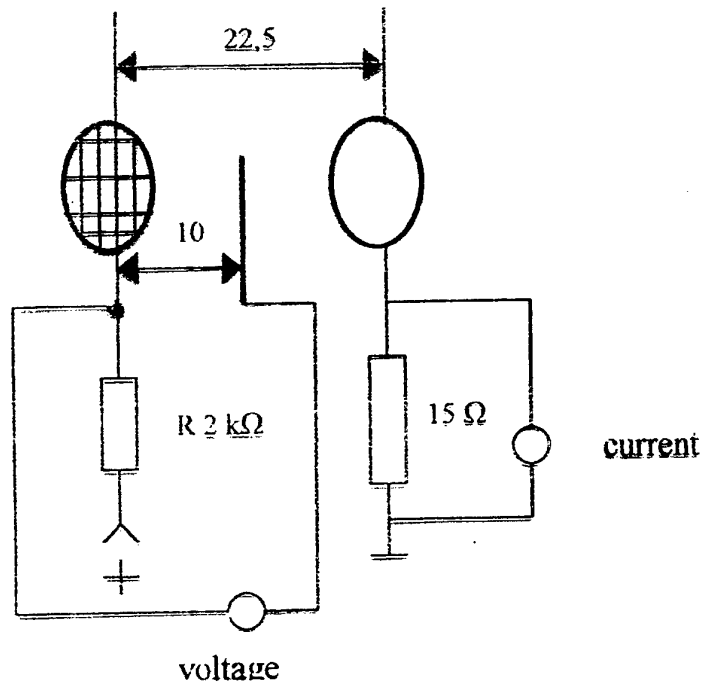


PROCEDURE FOR CALCULATION OF THE BREAKDOWN VOLTAGE  
FOR  $O_2(^1\Delta_g)$  CONTAINING MIXTURE



# The study of VCC

## Experimental set-up



# The study of VCC

## Experimental set-up

